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PURGING OF A TANK-MOUNTED MULTILAYER INSULATION SYSTEM BY GAS DIFFUSION

by Irving E. Sumner

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SUMMARY

An experimental investigation was conducted to determine the gaseous helium purge characteristics of a multilayer insulation (MLI) system mounted on a spherical liquid-hydrogen propellant tank 1.39 meters (4.57 ft) in diameter. The primary purpose of this investigation was to determine the time required to purge the condensible nitrogen gas, initially contained within the insulation panels, with the noncondensible helium purge gas by means of gas diffusion to obtain nitrogen gas concentrations of 1 percent or less.

The multilayer insulation consisted of two blankets; each blanket contained 15 double aluminized Mylar radiation shields alternated with double silk net spacers. The insulation system utilized six 60°-gore MLI panels on the sides of the test tank, one conical MLI panel on the top and one conical MLI panel on the bottom of the test tank in each blanket of insulation.

The gaseous nitrogen initially contained within the MLI system and vacuum chamber was purged with gaseous helium introduced both underneath the MLI panels and into the vacuum chamber itself. Insulation purge rates from 10 to 37 MLI system volumes per hour were used while the vacuum chamber purge rate was normally set at approximately 2.4 chamber volumes per hour.

The time typically required to purge the MLI panels to 1 percent gaseous nitrogen concentration was approximately 69 minutes for a conical panel on the top of the tank, 75 to 97 minutes for the 60°-gore panels on the sides of the tank, and 158 minutes for a conical panel on the bottom of the tank. Predictions of gaseous nitrogen concentration within the MLI panels made using the Systems Improved Numerical Differencing Analyzer (SINDA) computer program agreed reasonably well with the experimental data.

Four space-hold (vacuum) thermal performance tests with the test tank containing liquid hydrogen indicated that no significant thermal degradation of the MLI system had occurred due to the purge tests or other tests conducted. The final measured heat input attributed to the MLI was 7.23 watts (24.7 Btu/hr) as compared to 7.18 watts (24.5 Btu/hr) for the initial baseline thermal performance test.

INTRODUCTION

Within the last few years, the concept of a reusable cryogenic upper stage vehicle to be used to deliver and/or retrieve spacecraft from geosynchronous orbit has been proposed as a part of the Space Shuttle transportation system. Such an upper stage vehicle requires the use of multilayer insulation (MLI) to provide the necessary space-hold (vacuum) thermal protection for the cryogenic propellants carried on board the vehicle, particularly for near-earth orbital operations for time durations lasting a few days or longer. To be cost effective, the multilayer insulation on the propellant tanks must itself be reusable (ref. 1, for example). This requires that the multilayer insulation must be able to withstand exposure to different environments (both on the ground and in space) for at least several space flights. The insulation must also provide a relatively constant and predictable thermal performance from one space flight to the next during the required life expectancy of the insulation system.

An important factor in providing reliable reusability is adequate purging of the condensible gases (e.g., air, nitrogen, or water vapor) from within the multilayer insulation system before filling the propellant tanks with cryogenic propellants prior to launch. Failure to do so may result in condensed and frozen gases forming in the insulation which could cause either (1) the degradation of the highly reflective surfaces of the radiation shields, or (2) higher than normal interstitial pressures within the insulation after the vehicle has been placed in the vacuum environment of space. These conditions may lead to the physical deterioration of the insulation and/or an increase in the heat input through the insulation into the propellant tank.

Several previous investigations concerned specifically with purging of multilayer insulation systems are noted in references 2 to 5. Reference 5 is of particular interest in that experimental purge effectiveness data were obtained for a relatively large insulated propellant tank. Purge tests were conducted with a 2.23-meter- (7.30-ft-) diameter spheroidal liquid hydrogen tank insulated with 3.81-centimeter- (1.50-in.-) thick MLI and enclosed in a purge bag. The MLI consisted of double-goldized Kapton radiation shields separated by Dacron tuff spacers. The MLI was purged at a relatively high volumetric flow rate with gaseous helium injected at discrete points within the MLI panels by means of purge pins penetrating the insulation. The purge test results indicated that a 1 percent condensible gas concentration at the outlet of the purge bag could be achieved within 5 minutes. However, there was no indication of the condensible gas concentration actually achieved within the MLI panels or the uniformity of the gas concentration throughout the MLI system.

Several years ago, an experimental investigation was initiated at the Lewis Research Center to further explore the concept of reusable multilayer insulation for cryogenic space vehicles that could potentially be utilized with the Space Shuttle

Orbiter. This investigation was oriented to examine the reusable insulation concept from a different point of view than some of the investigations mentioned previously so that information could be generated across as broad a base as possible. Therefore, it was decided to experimentally test a MLI system utilizing double-aluminized Mylar (DAM) radiation shields because of the availability and low cost. Silk netting was used as the spacer material between radiation shields because it can be easily formed to conform with double-curved contour of the propellant tank surfaces which aids in good layer-density control of the insulation panels. In addition, the DAM/silk net insulation concept had been studied extensively in previous investigations (e. g., refs. 6 to 10) so that its thermal performance characteristics were well known. It was also decided to determine the insulation system purge characteristics while purging the MLI slowly by means of gas diffusion since (1) the concept of rapid purging had already been investigated (ref. 5), and (2) no further firm requirements for rapid purging of the insulation could be ascertained.

The experimental testing of this insulation system was divided into two phases. The first phase was to (1) examine the purge characteristics of the insulation system, and (2) determine if any degradation of the space-hold (vacuum) thermal performance of the MLI system had occurred as a result of the purge tests conducted. The second phase was concerned with subjecting the MLI system to a series of thermal cycles simulating the different environmental conditions (ground-hold, ascent, space-hold, and reentry) which might be imposed during a typical space mission with the vehicle in the Cargo Bay of the Space Shuttle Orbiter. The space-hold thermal performance of the insulation system was also experimentally determined after the MLI had been deliberately exposed to a 100 percent relative humidity environment.

This report presents experimental data obtained during the first phase of the test program to determine the purge characteristics of a DAM/silk net multilayer insulation system mounted on a 1.59-meter- (4.57-ft-) diameter spherical liquid-hydrogen propellant tank. The insulation system configuration was very similar to one that had already been tested for space-hold thermal performance (ref. 11). The insulation panels were purged with gaseous helium by means of gas diffusion, a technique that does not require the use of purge pins penetrating the insulation.

Several gaseous helium purge tests were conducted to determine the effect of purge gas flow rate and temperature on condensible (nitrogen) gas concentration within the MLI system. All purge tests were conducted with the insulated test tank mounted within a cylindrical vacuum chamber at 1-atmosphere pressure. The helium purge gas was introduced both underneath the MLI system and into the vacuum chamber which was assumed to represent the structural shell of a potential space vehicle. The experimentally measured gas concentrations obtained within the MLI panels were compared with analytical predictions. To make these predictions, the experimentally measured gas

concentrations at the edges of the MLI panels were used as an input to the analytical program. The program used was the Systems Improved Numerical Differencing Analyzer (SINDA) computer program. Vacuum chamber and MLI system pumpdown/repressurization tests were also conducted at ambient temperature (no liquid hydrogen in the propellant tank). The purge and pumpdown/repressurization tests were interspersed with four space-hold thermal performance tests conducted at vacuum conditions. Liquid hydrogen was contained in the propellant tank for these space-hold tests; the liquid hydrogen boiloff was utilized to determine if any degradation to the thermal performance of the MLI system had occurred.

Although test measurements were, in general, made in the U.S. customary system of units, the International System (SI) are the primary units utilized in this report.

EXPERIMENTAL APPARATUS

Test Tank

The liquid hydrogen test tank (shown in fig. 1) used in this test program was a spherical tank 1.39 meters (4.57 ft) in diameter and contained a volume of 1.42 cubic meters (50 ft^3). The tank was constructed of 2219-T62 aluminum. The upper and lower hemispherical shells of the tank were chemically milled to a membrane thickness of 0.094±0.013 centimeter (0.037±0.005 in.); the weld lands were 0.41 centimeter (0.16 in.) thick. The test tank had a working pressure of 3.4×10^5 newtons per square meter differential (50 psid). The tank was supported by three support brackets welded to the lower hemispherical shell.

The test tank incorporated a 0.3-meter- (1-ft-) diameter access opening and cover to allow access to the interior of the tank. The access cover had four ports to accommodate a vent line, a dip-tube fill and drain line, an instrumentation rake, and an electrical feedthrough.

Multilayer Insulation System

The multilayer insulation system installed on the liquid hydrogen test tank employed the same basic modular design as the MLI system previously tested for space-hold (vacuum) thermal performance and reported in reference 11. The basic insulation design concept utilized two MLI blankets (fig. 2) to cover and thermally protect the entire tank surface. Each blanket consisted of 15 double-aluminized Mylar (DAM) radiation shields alternately spaced with 16 double silk net spacers. A laminated, aluminized Mylar/Dacron scrim (reinforced Mylar) cover sheet was applied to each

side of each blanket. The layup of cover sheets, radiation shields, and silk net spacers for each MLI blanket was held together by Nylon button-pin studs spaced on approximately 20-centimeter (8-in.) centers.

The portion of the MLI blankets installed on the sides of the test tank were fabricated in the shape of gore panels with each blanket of MLI containing six 60°-gore panels (fig. 3). The panels were fabricated to conform to the nominal double-curved contour of the tank wall by using the following techniques:

(1) Forming the silk net spacers to the desired contour by wetting, stretching, and drying the silk netting on a male mold

(2) Partially forming the radiation shields by means of vacuum-forming in a female mold and then completing the forming to the desired contour by cutting, darting, and taping the aluminized Mylar on a male mold

(3) Partially forming the cover sheets by means of vacuum-forming in a female mold and then completing the forming to the desired contour by hand ironing the sheets over a male mold

MLI panels in the shape of truncated cones were used to thermally protect the top and bottom of the test tank. These panels were fabricated in a manner very similar to the 60°-gore panels with the exception that partial vacuum forming of the radiation shields and cover sheets was not required. Both the radiation shields and cover sheets were formed to the desired conical contour by simply cutting, darting, and taping flat sheets of the material over a male mold.

During assembly of the MLI panels, the Nylon button-pin studs were cemented to the exterior surfaces of the cover sheets at their points of contact to further provide a positive means of layer density control. The nominal insulation panel layer density was approximately 18 layers per centimeter (45 layers/in.). This value was based on the Nylon button-pin stud length of 0.95 centimeter (3/8 in.); the effective thickness of each of the cover sheets of approximately 0.025 centimeter (0.010 in.) was also accounted for.

Also added to the MLI 60°-gore panels during assembly were the items necessary to provide for installation of the panels on the test tank. These items included strips of Velcro hook and pile fastener and Nylon grommets. The location of the polyester Velcro fastener on the MLI gore panels is shown in figure 4. Short intermittent strips of Velcro pile 5.1 centimeters (2.0 in.) wide were adhesively bonded to the outer cover sheets adjacent to one edge of the panels for both the inner and outer blankets of insulation. Long continuous strips of Velcro hook 2.5 centimeters (1.0 in.) wide were adhesively bonded to the inward (toward the tank wall) facing portions of both the inner and outer cover sheets which extended beyond the edge of the MLI panels along each side as noted in figure 4(b).

Six Nylon grommets were also installed in each MLI gore panel (two near the top, two at the equator, and two near the bottom) as indicated in figure 5. The detail of the grommets is noted in figure 6. The grommets completely penetrated the insulation panels and were retained in place by means of the snap-on washers.

During assembly of the conical MLI panels for the top and bottom of the test tank, short strips of 2.5-centimeter- (1.0-in.-) wide Velcro fasteners were adhesively bonded to the inner and outer cover sheets of the panels. The general location of the Velcro strips for the MLI panels at the bottom of the test tank (for example) is shown in figure 7. No Nylon grommets were used for these conical MLI panels.

Installation of MLI Panels on Test Tank

Prior to the installation of the MLI panels, the following items (shown in fig. 8) were installed on the test tank: (1) vent and fill line tube connections, (2) two MLI gore panel purge rings, (3) two fiberglass cones, (4) two fiberglass cone purge tubes, (5) Velcro pile fastener, and (6) 36 Nylon positioning pins. The two circumferential purge rings were fabricated from 0.64-centimeter- (0.25-in.) diameter aluminum tubing. Each purge ring contained 24 pairs of holes 0.033 centimeter (0.013 in.) in diameter equally spaced around the circumference of the tank. The holes in each pair were located on opposite sides (top and bottom) of the purge ring to more evenly distribute the helium purge gas underneath the MLI gore panels. The upper and lower fiberglass cones were used to support the conical MLI panels at the top and bottom of the tank. These cones were perforated with 0.32-centimeter- (0.125-in.-) diameter holes spaced on 2.0 centimeter (0.80 in.) centers to allow passage of the helium purge gas. The two 0.64-centimeter- (0.25-in.-) diameter cone purge tubes distributed helium purge gas underneath the fiberglass cones and conical MLI panels at the top and bottom of the tank. The short, intermittent strips of 5.1-centimeter- (2.0-in.-) wide Velcro pile fastener adhesively bonded to the tank wall were one means of attaching the MLI gore panels to the sides of the test tank. The 36 Nylon positioning pins were utilized to properly locate the MLI gore panels on the test tank. The positioning pins also acted as a second means of attaching the gore panels to the tank. The base of each Nylon pin was adhesively bonded to the tank wall with the use of a fiberglass cloth overlay and a thermoplastic polyester resin adhesive (Pliobond 4001/4004). The detail of the Nylon positioning pin is shown in figure 9.

The normal tank fill and drain line elbow at the bottom of the tank (fig. 8) was blanked off and was not used for this test program. Not shown in figure 8 are the strips of Velcro pile fastener adhesively bonded to the fiberglass cones to mate with the Velcro hook fastener on the inner cover sheets of the inner blanket conical MLI

panels required for support of these panels.

The completed installation of the MLI system on the test tank is shown in figures 10 and 11. The installation of this system was also very similar to that described in reference 11. The inner blanket gore panels were installed as fabricated. The outer blanket gore panels, prior to installation, were cut back on the top and bottom (as shown in figs. 10 and 12) to mate with the outer blanket conical MLI panels in a standard butt joint. The inner cover sheets of the outer blanket gore panels, however, were left full length to fit over the Nylon positioning pins located near the top and bottom of the tank. The vertical butt joints between MLI gore panels for the inner and outer blankets of insulation were offset 6° as shown in figure 13 so that there would not be a direct path for thermal radiation to reach the tank wall. The overlapping cover sheets at each butt joint also provided additional protection from thermal radiation. Cutouts were made in all MLI gore panels to accommodate the penetration of the tank support brackets as shown in figure 14.

The conical MLI panels for the inner blanket of insulation were then installed on the top and bottom of the tank. The edges of these conical MLI panels were attached intermittently to the inner cover sheet of the MLI gore panels in the outer blanket with Velcro fasteners in a Y-type joint as shown in figure 12. The conical MLI panels in the outer blanket were then installed and mated with the MLI gore panels in the outer blanket with a standard butt joint with overlapping cover sheets.

Small five-layer MLI panels (positioning pin covers) were installed over the protruding Nylon positioning pins and tank support brackets near the tank equator (figs. 10, 11, 13, and 15) to prevent thermal radiation from reaching the tank directly. The positioning pin covers consisted of five radiation shields and six double silk net spacers with a reinforced Mylar cover sheet on each side. The positioning pin covers were held together with Dacron thread stitched around the outside edges. The covers were attached to the MLI gore panels of the outer blanket by means of Velcro fastener and aluminized Mylar tape.

Installation of Test Tank in Vacuum Chamber

All tests were conducted with the insulated test tank mounted within a cylindrical vacuum chamber 1.83 meters (6.00 ft) in diameter by 3.12 meters (10.25 ft) high. Three 0.25-meter (10-in.) oil diffusion pumps provided a vacuum capability in the low 10^{-3}-newton-per-square-meter (10^{-5}-torr) range at ambient temperature conditions and in the low 10^{-4}-newton-per-square-meter (10^{-6}-torr) range with the test tank filled with liquid hydrogen.

The insulated test tank was suspended from a tubular, stainless-steel support ring

by means of six stainless-steel wire support struts 0.24 centimeter (0.094 in.) in diameter and 24.0 centimeters (9.46 in.) long (fig. 14). The tubular support ring was, in turn, suspended from the lid of the vacuum chamber by means of six support rods as shown in figure 16. The insulated test tank was enclosed within an electrically heated cylindrical shroud. The temperature of the shroud could be maintained within ±1.1 K (2.0° R) of a desired temperature during the helium purge tests and the space-hold thermal performance tests. The shroud consisted of five curved, aluminum panels on the sides and two flat aluminum panels on both the top and bottom. The vertical joints between adjacent side panels and the horizontal joints between the semicircular top and bottom panels were (1) open to allow purge gases to flow into and out of the shroud, and (2) optically dense so that no direct thermal radiation from the vacuum chamber wall could reach the outer surface of the insulation system. The shroud was bolted to the tank support ring for support.

A liquid hydrogen cold guard 0.76 meter (2.5 ft) in diameter and 0.51 meter (1.67 ft) high was located above the test tank as shown in figures 16 and 17. The purpose of the cold guard was to minimize any extraneous heat leaks to the test tank during the space-hold thermal performance tests. The cold guard was insulated with two blankets of MLI in very much the same manner as the test tank. All purge tubing and instrumentation wiring that lead to instrumentation located on or within the test tank was thermally shorted directly to the wall of the cold guard. The test tank vent and fill lines passed directly through the cold guard to minimize extraneous heat leaks from this source. The cold guard contained a sufficient volume of liquid hydrogen such that it did not require refilling during a 4½-day-long space-hold thermal performance test.

Lead wires for temperature sensors (thermocouples) located within the MLI system were thermally conditioned by running the wires along the reinforced Mylar cover sheets to which the sensors were attached all the way to the top of the test tank, up the vent line and then to the top of the cold guard before the wires were brought out from within the insulation system. Lead wires to temperature sensors located on the outside surface of the MLI system were not thermally conditioned since the outer surface temperature of the insulation was very close to the ambient shroud temperature during the purge and space-hold thermal performance tests.

Purge Gas System

The purposes of the purge gas system were to allow (1) purging of the MLI on both the test tank and the cold guard with gaseous helium, (2) purging of the vacuum chamber with either gaseous helium or gaseous nitrogen, and (3) repressurization of both

the MLI and vacuum chamber from vacuum conditions to 1 atmosphere pressure with either gaseous helium or gaseous nitrogen. A schematic of the purge system utilized for this test program is shown in figure 18. Helium purge gas was distributed to the two purge tubes and two purge rings located underneath the MLI on the test tank from a common MLI purge manifold. Four flow-control orifices, ranging in size from 0.0292 to 0.0318 centimeter (0.0115 to 0.0125 in.), depending upon the MLI system volume to be purged, were used to distribute the purge gas in the volumetric flow rates desired to each purge tube and purge ring. The range of flow-control orifice diameters was such that the purge gas volumetric flow rates to the four arbitrarily defined purge regions in the MLI system (shown in fig. 19) was relatively uniform on the basis of MLI system volumes per unit time. The calculated volume of each purge region shown in figure 19 was the volume between the outer surface of the insulation and the wall of the test tank. Since a common purge manifold and choked-flow orifices were used to meter the helium purge gas to each purge region, the volumetric flow through each flow-control orifice can be compared by looking at the relative values of the orifice diameters and discharge coefficients. A separate flow-control orifice was provided for the purge ring located on the cold guard.

A purge gas heater with a 300-watt (1020-Btu/hr) electrical heating capability was installed between the cold guard and the test tank. The purpose of this heater was to heat the helium purge gas for the MLI system on the test tank up to a temperature of 350 K (630° R) for those tests where this was desired.

The vacuum chamber could be purged separately with either gaseous helium or gaseous nitrogen. Again flow-control orifices were used to provide a specified flow rate of either gas.

Two motor-driven flow control valves were also installed in the purge system to repressurize the MLI system and vacuum chamber from vacuum conditions to 1 atmosphere pressure. The flow control valves provided a flow rate versus valve position calibration over a range of flow rates of greater than 10^6 to 1. This was required in order to provide a reasonable simulation of the reentry pressure profile that might be expected to be present in the cargo bay of the Space Shuttle Orbiter from an altitude of approximately 122 000 meters (400 000 ft) to sea level (ref. 12).

MLI Gas Sampling System

The purpose of the MLI gas sampling system, shown in figure 20, was to provide a means of determining the purge gas concentration within the MLI system during the purge tests. This system was very similar to that used previously in reference 13. Twelve gas sampling tubes were provided to withdraw samples of purge gas from within the MLI system. Six tubes were used to obtain gas samples at butt joints between

adjacent MLI panels to determine the time-dependent boundary conditions at the edges of the panels. The other six tubes were used to obtain samples of purge gas from within MLI panels between the radiation shields. The sampling tubes within a given MLI panel and at an adjacent butt joint were paired together for purposes of obtaining experimental data. The operating procedure for the gas sampling system was such that the gas sample obtained from within a given MLI panel was analyzed for gas concentration by one thermal conductivity cell at the same time as the gas sample obtained from the adjacent butt joint was analyzed by a second thermal conductivity cell. This pairing of gas sampling tubes, or locations within the MLI system, is indicated, in general, in figure 20. The specific gas sampling locations is shown in figure 21. The gas sampling tubes were inserted laterally into the MLI system through the butt joints as indicated in figure 22. The six tubes used to obtain gas samples from within the MLI panels themselves were located between the two silk nets between the two outer radiation shields in each panel to minimize any degradation to the thermal performance of the insulation system. Outside of the panels, the gas sample tubes were attached to the outer cover sheet of the outer MLI blanket with aluminized Mylar tape. All of the gas sampling tubes were 0.102 centimeter (0.040 in.) outside diameter by 0.015 centimeter (0.006 in.) wall thickness stainless-steel tubes to minimize any disturbance to the MLI panels. The tubes were all approximately the same length (3.66 m (12.0 ft)) to provide the same gas flow characteristics for a given gas concentration.

The gaseous nitrogen concentration of the gas samples from the individual gas sampling tubes was sensed by two commercial thermal conductivity cells, one for the gas samples obtained at the butt joints and one for the gas samples obtained from within the MLI panels. The thermal conductivity cells were immersed in an ice bath to provide a relatively constant temperature environment. The gas sample from each gas sampling tube was drawn through the sample sides of the thermal conductivity cells as shown in figure 20. Small diameter tubing (0.11 cm (0.044 in.) i.d.) from the lid of the vacuum chamber up to the needle valves, and pneumatic valves having a small internal volume, were used throughout the gas sampling system to minimize the time response of the flow system. This made it possible to withdraw only a small volume of sample gas from within the MLI system so that gas concentrations within the insulation would not be significantly affected by previous samples of gas withdrawn.

Gaseous helium for the reference sides of the thermal conductivity cells, as well as known mixtures of gaseous helium and nitrogen for calibration purposes for the sample sides of the cells, were supplied through 0.102 centimeter (0.040 in.) outside diameter by 0.015 centimeter (0.006 in.) wall thickness tubes 3.66 meters (12.0 ft) long to duplicate the pressure drop in the actual gas sampling tubes. These gases were supplied to the gas sampling system at pressures just slightly greater than 1 atmosphere to duplicate the pressure in the vacuum chamber during a purge test. The

low-cracking-pressure check valves acted as pressure relief valves to vent gas flows from the facility supplies that were in excess of the flows set through the thermal conductivity cells. The check valves had a nominal cracking pressure of 1.0×10^{3} newtons per square meter (0.15 psi). The facility gaseous helium flows through both the sample and reference sides of the thermal conductivity cells were initially set at 15±0.3 standard cubic centimeters per minute (0.92±0.02 standard cu in./min) by adjustment of the needle valves downstream of the cells.

Twelve 0- to 1.4×10^{3}-newton-per-square-meter differential pressure (0- to 0.2-psid) pressure transducers were provided to obtain an indication of the differential pressure from points within the MLI panels to the ambient vacuum chamber pressure during the purge tests.

Instrumentation

The two thermal conductivity cells were used to determine the gaseous nitrogen concentrations within the MLI system during the purge tests. Periodic calibrations of the cells were made throughout the test program by using known mixtures of gaseous helium and nitrogen as determined by an analytical mass spectrometer. The thermal conductivity cells had a relatively poor sensitivity to variations in gaseous nitrogen concentration above 40 percent. But they did have a relatively good sensitivity, as well as a nearly linear calibration, for gaseous nitrogen concentrations below 20 percent, which was the primary range of interest. Some drift of the zero and full-scale outputs of the cells was noted during the steady-state calibrations and transient data taking. This effect was minimized by zeroing and spanning the output frequently while flowing helium and nitrogen, respectively, through the sample sides of the thermal conductivity cells. In general, the error due to drift that was expected to occur during the purge tests was less than 3 percent gaseous nitrogen concentration while measuring nitrogen concentrations near 100 percent and less than approximately 0.3 percent nitrogen concentration while measuring concentrations near 0 percent. The dynamic response of the output of the thermal conductivity cells to a step change in gas concentration (as determined experimentally) approximated a second-order system having a time constant of 0.0855 minute; this response was virtually identical to that reported in reference 13. The dynamic error anticipated during a linear change in gaseous nitrogen concentration of 0.05 percent per minute, for example, would be approximately 0.02 percent nitrogen concentration for a second order system having a time constant of 0.0855 minute. Therefore, the dynamic error was small compared to the anticipated error due to drift, and no corrections for instrument error due to dynamic response were applied to the experimental data. The gas flow through each sampling

tube was allowed to continue for 1.0 minute for each data point. The dead time was approximately 0.23 minute from the time that the gas sample selection valves were cycled from one pair of gas sampling tubes to the next until the time that the output of the thermal conductivity cells started to respond. Therefore, a time interval of approximately eight time constants was allowed for the output of the thermal conductivity cells to reach their final reading.

Temperatures of the MLI blankets as well as of the constant-temperature shroud, the warm ends of the tank support struts, the Nylon positioning pins and the purge gases were measured with Chromel-Constantan thermocouples. The 26 thermocouples used to determine the MLI temperatures were grouped in six groups of four thermocouples in each group to measure the temperature profiles across the two MLI blankets; two additional thermocouples were used to measure the temperature on the inside surfaces of two of the positioning pin covers. These thermocouples were fabricated from 0.020-centimeter- (0.008-in.-) diameter wire. The thermocouple junctions were adhesively bonded to the reinforced Mylar cover sheets of the MLI panels with double-stick Mylar tape for a length of approximately 2.5 centimeters (1.0 in.). The thermocouple junctions and lead wires for a length of approximately 15 centimeters (6 in.) were then taped to the cover sheet with aluminized Mylar tape. The thermocouple leads from the thermocouples located on the inner MLI blanket and the inner cover sheet of the outer blanket were further thermally conditioned by running the wires along the cover sheets to which the junctions were attached up to the top of the test tank, along the vent line insulation and up to the top of the cold guard. The leads were then withdrawn from the cold guard insulation and routed to electrical feedthroughs in the lid of the vacuum chamber. The reference junctions for all of the Chromel-Constantan thermocouples were immersed in a liquid nitrogen bath. The temperature measurements provided by these thermocouples had a probable error of ±4.0 K (±7.2° R) at liquid hydrogen temperature. This error was a minimum of ±0.83 K (±1.5° R) at approximately 140 K (252° R) and then increased to ±2.3 K (±4.2° R) at room temperature.

Additional temperature measurements within and on the wall of the test tank, at the cold ends of the tank support struts, on the vent and fill lines, and within the cold guard were obtained using platinum resistance thermometers to improve the accuracy of these measurements. For the resistance thermometers within, on, or near the test tank, the copper lead wires were thermally conditioned by adhesively bonding them to the wall of the cold guard before the leads were routed to the electrical feedthroughs in the lid of the vacuum chamber. These temperature measurements had a probable error from ±0.07 K (±0.12° R) to ±1.26 K (±2.27° R) at liquid hydrogen temperature depending upon the temperature range of the electrical bridge circuit employed. These ranges varied from 20 to 26.7 K (36° to 48° R) to 20 to 111 K (36° to 200° R).

Test tank, cold guard, and vacuum chamber pressures, as well as purge gas pressures upstream of the flow-control orifices, were measured with bonded strain gage transducers which had an estimated uncertainty of ±0.25 percent of full scale. Vacuum levels within the vacuum chamber were also measured by means of thermocouple gages and ionization gages. The ionization gages were located on the wall of the vacuum chamber as well as within the constant temperature shroud.

The 12 differential pressure transducers installed in the gas sampling system (fig. 20) to measure the pressure differential from points within the MLI system were capacitance-type transducers that (1) had a range of 0 to 1.4×10^{3} newton per square meter differential (0 to 0.2 psid) and (2) had a low external leakage when vacuum conditions were imposed on both sides of the diaphragm. These transducers had an estimated uncertainty of approximately ±5 percent of full scale.

Mass flowmeters were used to measure the liquid hydrogen boiloff rate (range from 0 to 0.057 standard cu m/min (0 to 2 standard cu ft/min)) and the gaseous helium flow through the gas sampling system (range from 0 to 50 standard cu cm/min (0 to 3.05 standard cu in./min)). The uncertainty associated with these meters was ±0.5 percent of full scale.

Control Systems

The temperature of the constant-temperature shroud enclosing the insulated test tank was controlled in a closed-loop mode by four separate alternating current electrical heating circuits having a total capacity of approximately 10 000 watts (34 000 Btu/hr). The shroud was divided into four heating zones; top, bottom, and upper and lower halves of the cylindrical walls. The top and bottom zones each utilized two silicon rubber heating blankets wired in parallel. The upper and lower zones of the cylindrical walls each had five heating blankets wired in parallel (one blanket per zone on each of the five side panels). Temperature control of the shroud during the space-hold thermal performance tests was maintained at 300±1 K (540±2° R).

Temperature control of the purge gas heater was also provided in a closed-loop mode by means of a 300 watt (1020 Btu/hr) silicon rubber heater and controller.

Repressurization of the MLI system and vacuum chamber from vacuum conditions to 1 atmosphere absolute pressure was accomplished by means of the flow control valves (fig. 18). The flow control valves, driven by AC synchronous motors, were opened on a preselected schedule so that (1) purge gas flow rates into the MLI system and vacuum chamber would be controlled in an attempt to provide a slight positive pressure within the MLI system, and (2) the pressure rise rate in the vacuum chamber would approximate that to be expected in the cargo bay of the Space Shuttle Orbiter (ref. 12).

The test tank and cold guard pressures were maintained at a constant level during the space-hold thermal performance tests by separate closed-loop control systems. These pressure-control systems used high-resolution, differential-pressure, capacitance transducers which sensed very small pressure variations inside the tanks relative to an absolute reference pressure. The electrical output signals from the transducers were used as input signals to control units for motorized valves in the test tank and cold guard vent lines. The motorized valves, in turn, regulated the liquid-hydrogen boiloff flow rates to maintain the tank pressures at constant values. This system maintained the tank pressures to within 5.5 newtons per square meter (0.0008 psi) of a desired value. In addition, the cold guard pressure was maintained between 70 and 210 newtons per square meter (0.01 to 0.03 psi) above the test tank. This tank pressure-control system is discussed in more detail in reference 14.

DATA RECORDING

Most of the experimental data was recorded by means of a high-speed digital data system. Additionally, some of the data, such as tank and vacuum chamber pressures, liquid-hydrogen boiloff rate, shroud temperatures, output of the capacitance-type, differential pressure transducers in the tank pressure - control system, and the output of the thermal conductivity cells in the gas sampling system were recorded on strip charts in the control room. A small amount of data was also recorded by hand from digital panel meters located in the control room.

TEST PROCEDURE

Purge Tests

Prior to the start of each gaseous helium purge test, the vacuum chamber was evacuated to a vacuum level of about 10 newtons per square meter (1×10^{-1} torr) or less to purge the MLI system and vacuum chamber of any gases remaining from the previous tests. The chamber was then slowly backfilled with clean, dry gaseous nitrogen to 1 atmosphere absolute pressure over a period of about 1 hour. The gaseous helium flow rate through both the sample and reference sides of the thermal conductivity cells was set at 15±0.3 standard cubic centimeters per minute (0.92±0.02 standard cu in./min). Gas samples were taken from within the MLI system to check the gas sampling system valve operation and confirm the presence of 100 percent nitrogen gas. The purge system gas supply pressures were set to provide the desired purge gas flow rates, and the shroud heater and purge gas heater controllers were set at either 300 or

350 K (540° or 630° R) depending upon the test requirements. For test 6B, the shroud and purge gas heaters were set at 350 K (630° R) and were turned on approximately 1½ hours prior to the start of the purge test. For most other purge tests conducted, the shroud and purge gas heaters were set at 300 K (540° R) and were turned on at the start of the purge test (purge gas heater alone was set at 350 K (630° R) for Test 6A). At the start of the purge test, the MLI system and vacuum chamber purge flows were started simultaneously; the purge gases were vented near the bottom of the vacuum chamber. Purge gas samples from within the MLI system were withdrawn for 1 minute each through the 12 gas sampling tubes at fairly regular intervals during the purge test. These intervals were generally either 1/2 or 1 hour. The purge tests were generally continued for a period of 3 to 4 hours to insure that the gaseous nitrogen concentrations at all of the gas sampling locations had been reduced to less than 1 percent.

Repressurization Tests

Two repressurization tests were conducted with the vacuum chamber initially at a vacuum level as low as 10^{-2} newton per square meter (10^{-4} torr). The flow lines in the purge system between the vacuum chamber isolation valves (air-operated two-way valves) and the two flow control valves (shown in fig. 18) were vacuum purged prior to the start of the test. The gaseous helium (and nitrogen, if used) supply pressures were set to the desired values. The three oil diffusion pumps were then valved off, and the repressurization sequence was started. The flow control valves were opened on a predetermined schedule to provide a rate of increase of the pressure in the vacuum chamber to approximate that expected in the cargo bay of the Space Shuttle Orbiter. When the chamber pressure reached 1-atmosphere absolute pressure, the chamber vent valve was opened, and the test was terminated.

Space-Hold Thermal Performance Tests

The space-hold (vacuum) thermal performance tests were the only tests reported herein in which liquid hydrogen was actually contained within the test tank. These tests, conducted under vacuum conditions (3.1×10^{-4}-N/m^2 (2.3×10^{-6}-torr) vacuum level or lower), utilized the measurement of the liquid hydrogen boiloff to determine the thermal performance of the multilayer insulation system. A description of the procedure used in conducting these tests can be found in reference 14.

ANALYTICAL MODEL

An analytical model to predict the gaseous nitrogen concentration within the MLI panels as a function of time was formulated assuming that the basic gas diffusion process was the only means by which mass transfer occurred in between radiation shields. The differential equation describing the gas diffusion process is of the following form (ref. 13):

$$\frac{\partial C_A}{\partial t} = D_{AB}\nabla^2 C_A \tag{1}$$

where

C_A molar density of gas A

D_{AB} diffusion coefficient of gases A and B, m^2/min (ft^2/min)

t time, min

Even though the solution of equation (1) can be written in terms of an infinite series for a two-dimensional diffusion process, difficulties were encountered when the numerical integration necessary to obtain the coefficients of the series was performed. Instead, a finite-difference numerical technique was used to solve equation (1).

The calculations were made using the Systems Improved Numerical Differencing Analyzer (SINDA) computer program (refs. 15 and 16). SINDA is intended primarily for analyzing thermal systems represented in electrical analog, lumped parameter form, although its use can be extended to include other physical systems governed by diffusion-type equations.

The MLI panel configurations used in the analytical model are shown in figures 23 and 24 for the conical panels and the 60^o-gore panels, respectively. For the conical panels, a wedge-shaped segment was used (fig. 23(a)). Gas diffusion was assumed to occur only through the open edge around the outer circumference of the segment and laterally between the radiation shields in the radial direction within the segment. The other three edges were assumed to be sealed, and no gas diffusion was accounted for in the circumferential direction due to the symmetry of the conical panels about the vertical centerline. Six nodes, equally spaced radially, were used with five being within the segment and one being at the open edge.

The complete 60^o-gore panel from the outer insulation blanket was used for the analytical model (fig. 24(a)). Gas diffusion was assumed to occur at the open edges on all four sides of the panel and in circumferential directions both vertically and horizontally within the panel. Forty-two nodes were used within the panel and

26 nodes were used around the edges of the panel.

The measured values of the gaseous nitrogen concentration obtained at the butt joints during purge tests of the MLI system were used as the boundary conditions at the edges of the MLI panels for the analytical model. Values of nitrogen concentration for nodes along the edges of the 60°-gore panel where no measurements were actually made were interpolated linearly from values at locations where measurements were made. The values of the diffusion coefficient used in the calculations were (1) 4.12×10^{-3} square meter per minute (4.43×10^{-2} ft^2/min) which is the analytical value for a mixture of helium and nitrogen gas (ref. 13), and (2) 5.30×10^{-3} square meter per minute (5.70×10^{-2} ft^2/min) which is the value found to be appropriate for a DAM/silk net MLI panel with the helium purge gas flowing through a closely spaced butt joint (also ref. 13). The number of nodes used in the analytical models was varied for several computer runs to check the variation in the predicted gaseous nitrogen concentration within the panels. The numbers shown in figures 23 and 24 of six nodes for the conical panels and 68 nodes for the 60°-gore panel were sufficient to eliminate this as a variable in the program.

DATA REDUCTION

The purge gas flow rates for the MLI system and the free volume of the vacuum chamber were calculated in terms of both mass flow rate and volumetric flow rate. The volumetric flow rate was calculated from

$$\dot{\nu} = \frac{\dot{m}}{\left(\frac{P}{RT}\right)V} \tag{2}$$

where

$\dot{\nu}$ volumetric flow rate, either MLI system (vol/hr) or vacuum chamber (vol/hr)

$\dot{m}$ mass flow rate, kg/hr (lbm/hr)

P vacuum chamber pressure, N/m^2 abs (psia)

R gas constant, J/kg-K (ft-lbf/lbm-°R)

T average temperature of either MLI or shroud, K (°R)

V specific volume of either MLI system, 0.186 m^3/MLI vol (6.58 ft^3/MLI vol) or vacuum chamber free volume, 5.695 m^3/chamber vol (201.1 ft^3/chamber vol)

The heat input into the test tank during the space-hold thermal performance tests was calculated from

$$Q = \dot{\omega}\lambda\left(\frac{\rho_L}{\rho_L - \rho_{SV}}\right) + \dot{\omega}(h_{TV} - h_{SV}) \tag{3}$$

where

Q	heat input, W (Btu/hr)
$\dot{\omega}$	measured liquid hydrogen boiloff mass flow rate, kg/hr (lbm/hr)
λ	latent heat of evaporation, W-hr/kg (Btu/lbm)
ρ_L	density of saturated liquid hydrogen, kg/m^3 (lbm/ft^3)
ρ_{SV}	density of saturated hydrogen vapor, kg/m^3 (lbm/ft^3)
h_{TV}	enthalpy of hydrogen vapor near tank vent location, W-hr/kg (Btu/lbm)
h_{SV}	enthalpy of saturated hydrogen vapor, W-hr/kg (Btu/lbm)

The density ratio factor is a correction for the liquid hydrogen boiloff that was not vented from the tank, but merely occupied the space vacated by the evaporated liquid. The calculations for miscellaneous heat inputs into the test tank and for other parameters unique to the space-hold thermal performance tests are discussed in reference 14.

RESULTS AND DISCUSSION

The basic test sequence of the test program reported herein is shown in table I. The various purge tests were interspersed with space-hold thermal performance tests under vacuum conditions to determine if anything done during the conduct of the purge tests had degraded the thermal performance of the insulation system.

Baseline Space-Hold Thermal Performance Test

The first test (Test 1) was conducted to determine the baseline heat inputs into the test tank and through the multilayer insulation. During the test, a vacuum level of approximately 1.3×10^{-4} newton per square meter (1×10^{-6} torr) within the shroud and 2.7×10^{-4} newton per square meter (2×10^{-6} torr) within the vacuum chamber was maintained. The total measured heat leak into the test tank was 8.52 watts (29.1 Btu/hr) of which 7.18 watts (24.5 Btu/hr) was attributed directly to the multilayer insulation.

A more complete description of these test results is given in reference 14.

Initial GHe Purge Tests (Tests 2A to 2D-1)

The initial gaseous helium purge test conducted was Test 2A (table I). The MLI gaseous helium purge rate was 6.7 MLI system volumes per hour while the vacuum chamber purge rate was intended to be 2.4 chamber volumes per hour. However, due to leakage of purge gas past the seal at the lid of the vacuum chamber, the test was unsatisfactory. (Mention of this test is included here so that the complete test history of the MLI system is documented.) For all remaining purge tests, the lid was bolted to the cylindrical section of the vacuum chamber, and no further leakage past the seal for the lid was observed.

The nitrogen gas concentrations measured at 8 of the 12 gas sampling locations within the MLI system are shown in figure 25 for Tests 2B, 2C, and 2D-1. The test results are shown for four butt joint locations (figs. 25(a) to (d)) and four locations within the MLI panels (figs. 25(e) to (h)). The remaining two butt joint locations and two MLI panel locations (two in the upper half of the gore panel, outer blanket, and two in the lower half of the gore panel, inner blanket; fig. 21) not shown in figure 25 provided test results that were similar to the next adjacent pairs of gas sampling tubes. These experimental data indicated that the test results were repeatable in like locations within the MLI system and that little distinction could be made for test results obtained within the inner and outer insulation blankets in a given location. The gaseous helium purge rates within the MLI system were varied from 10.1 to 36.8 MLI volumes per hour while the vacuum chamber purge rate was fixed at approximately 2.4 chamber volumes per hour. Overall, the test results indicated that gaseous nitrogen concentrations well below 1 percent could be achieved everywhere within the MLI system. The test results also indicated, in general, little decrease in the time required to achieve 1 percent nitrogen concentration when the MLI purge rate was increased from 10.1 to 20.2 MLI volumes per hour, but approximately a 30 to 40 percent decrease in the time required when the MLI purge rate was further increased to 36.8 MLI volumes per hour. These test results are not entirely consistent in that distinctly different rates of decreasing gaseous nitrogen concentration should have been observed for all three MLI purge rates as was the case for the results obtained for a flat, rectangular MLI panel with a butt joint (ref. 13). The inconsistencies that were observed in these test results may have been a consequence of some slight shifting of the MLI panels as the insulation system was subjected to the purge, pumpdown, and repressurization cycles during the conduct of the individual purge tests. Any shifting of the MLI panels could cause variations in the width of the gap at the butt joints between the edges of the panels. Varia-

tions in the width of the gap were believed to have been responsible for a variation in the measured nitrogen gas concentrations in purge tests previously conducted with a flat, rectangular MLI panel containing a butt joint (ref. 17).

For the gas samples obtained at the butt joints, the test results indicated that, in general, the gaseous nitrogen concentration was reduced most rapidly at the butt joints along the sides of the MLI gore panels (both upper and lower halves). A value of 1 percent gaseous nitrogen concentration was reached within 62 minutes or less (figs. 25(b) and (c)). The time required was somewhat longer for the butt joint between the gore panel and the upper conical MLI panel (70 min or less, fig. 25(a)). The time required was the longest for the butt joint between the gore panel and the lower conical MLI panel (106 min or less, fig. 25(d)).

For the gas samples obtained within the MLI panels, however, the gaseous nitrogen concentration within the upper conical panel was reduced the most rapidly, reaching a 1 percent nitrogen concentration within 74 minutes or less (fig. 25(e)). The purging of the upper conical MLI panel is very probably aided, to some extent, by the natural buoyancy of the helium purge gas enhancing the gas diffusion process. The purge times to achieve 1 percent gaseous nitrogen concentration within the gore panels were 87 and 103 minutes, or less, for the upper and lower halves, respectively (figs. 25(f) and (g)). The purge time for the lower conical MLI panel was again the longest, requiring a maximum of 168 minutes to reach 1 percent nitrogen concentration (fig. 25(h)).

The test results for Test 2D-1 alone are shown in figures 26(a) to (d) where the gaseous nitrogen concentration within the MLI panels can be compared with that of the adjacent butt joint. The nitrogen concentration within the upper conical MLI panel was reduced more rapidly than the concentration at the adjacent butt joint for the first 42 minutes of the purge test (fig. 26(a)). The author believes that this again indicates that the gas diffusion process was aided by the natural buoyancy of the helium gas flowing into the trapped volume between the radiation shields of the upper conical panel. For the remaining gas sampling locations, the nitrogen concentrations at the butt joints were reduced at a faster rate than was the concentration within the MLI panels (figs. (b) to (d)), as would be expected.

Also shown in figure 26 are the calculated gas concentrations within the MLI panels at the same locations as for the measured values. The values of the diffusion coefficient used in the calculations were 4.12×10^{-3} square meter per minute (4.43×10^{-2} ft^2/min) which is the analytical value for a mixture of helium and nitrogen gases (ref. 13) and 5.30×10^{-3} square meter per minute (5.70×10^{-2} ft^2/min) which is the value found to be appropriate for a DAM/silk net MLI panel with the helium purge gas flowing through a closely spaced butt joint (ref. 13). The predicted concentration within the upper conical MLI panel indicated a slower rate of reduction in the nitrogen concentration for

approximately the first 40 minutes of the purge test than was actually measured (fig. 26(a)). This appears to be due, again, to the fact that the analytical model did not account for any natural buoyancy of the helium purge gas aiding the gas diffusion process. After the first 40 minutes of the purge test, both the predicted and measured rates of reduction in the nitrogen concentration appear to be about the same. During this later period of time, the vacuum chamber, as well as the MLI panel, contained primarily gaseous helium, and further reductions in the nitrogen concentration appear to have been accomplished almost entirely by gas diffusion alone. The predicted gaseous nitrogen concentration as a function of time was always greater than the measured value at any given time, then, because the buoyancy of the helium purge gas in the gaseous nitrogen background for the first 40 minutes was not accounted for.

The predicted nitrogen concentrations for the upper and lower halves of the MLI gore panel as a function of time compare more favorably with the measured values (figs. 26(b) and (c)). A slower rate of reduction in the predicted concentrations was noted for only the first 20 to 30 minutes (approximately). This would indicate that, while the purge process occurring in the gore panel was still aided somewhat by the natural buoyancy of the helium purge gas in the early part of the purge test, it was not aided nearly as much as for the upper conical MLI panel. The predicted gaseous nitrogen concentration was greater than the measured values for approximately the first 80 minutes for the purge test for a diffusion coefficient of 5.30×10^{-3} square meters per minute (5.70×10^{-2} ft^2/min).

The predicted nitrogen concentrations as a function of time for the lower conical MLI panel agreed reasonably well with the measured values (fig. 26(d)). In this region of the insulation system, the natural buoyancy of the helium purge gas did not enhance the normal gas diffusion process.

Additional GHe Purge Tests (Tests 2D-2 to 6B)

Seven additional purge tests were conducted with the MLI system. The purpose of these tests (table I) was to investigate (1) the repeatability of the test results and the effect of the gas sampling interval (Tests 2D-2, 4A, 4B, and 6A), (2) the effect of purging the vacuum chamber with gaseous nitrogen rather than gaseous helium (Test 2E-1), (3) the effect of purging the vacuum chamber at a reduced flow rate with gaseous helium (Test 2E-2), (4) the effect of repressurizing the MLI system from vacuum conditions (Tests 4A and 4B), and (5) the effect of 344 K (620° R) temperatures imposed on the MLI during purging (Test 6B). The purge test results for all of these tests except Test 2E-1 (which will be discussed later) are shown in figures 27 (a) to (h).

Test 2D-2 was a repeat of the test conditions imposed on the insulation system for

Test 2D-1 with the time interval between periods of gas sampling increased substantially. The test results for Test 2D-2 indicated that the gaseous nitrogen concentrations of both the butt joints and within the MLI panels was reduced at a slower rate than for Test 2D-1. These results, however, are again believed to be due to some slight shifting of the insulation panels which changed the width of the gaps at the butt joints between insulation panels, and are not due to the gas sampling interval. Two reasons for this belief are that (1) subsequent purge tests (Tests 4A, 4B, and 6A) with different sampling intervals for the same basic test conditions indicated only minor variations in the rate of reduction in the gaseous nitrogen concentration, and (2) purge tests with flat insulation panels with identical test conditions and varying gas sampling intervals in which the same basic type of gas sampling system was utilized (refs. 13 and 17) indicated that the test results were independent of the gas sampling interval for periods of time ranging from 20 to 60 minutes. The times required to reach 1 percent gaseous nitrogen concentration within the MLI panels for Test 2D-2 were approximately 69 minutes for the upper conical MLI panel, 75 minutes for the upper half of the gore panel, 97 minutes for the lower half of the gore panel, and 158 minutes (extrapolated) for the lower conical MLI panel. These times were not significantly different from those mentioned previously for lower MLI purge rates of 10.1 and 20.2 MLI volumes per hour.

The time-dependent boundary conditions at the butt joints of the MLI panels for Test 2D-2 (figs. 27(a) to (d)) were again used as an input to the SINDA computer program to provide calculated values of the nitrogen concentrations within the MLI panels as a function of time. These calculated results, obtained using a value of 5.30×10^{-3} square meters per minute (5.70×10^{-2} ft^2/min) for the diffusion coefficient, are shown in figures 27 (e) to (h). The agreement between the calculated and experimental results shows much the same trends, but is somewhat better than was noted for Test 2D-1 (fig. 26). The simplified analytical treatment assuming only a gas diffusion process and neglecting any natural buoyancy effects appears to be adequate for determining at least representative gas concentrations within the MLI panels as a function of time once the boundary conditions at the edges or butt joints of the panels has been specified.

Test 2E-1 was a purge test in which the MLI system was purged with gaseous helium, while the vacuum chamber was purged with gaseous nitrogen as noted in table I. The purpose of this test was to determine if the MLI system helium purge alone could adequately purge the MLI system of gaseous nitrogen. The test results indicated that the nitrogen concentrations achieved at either the butt joints (fig. 28(a)) or within the MLI panels (fig. 28(b)) in the upper half of the MLI system could not be reduced below 30 percent, even after 5½ hours of purging. The nitrogen concentrations were even higher (~50 percent) for the lower half of the MLI system; this was probably due to the helium tending to flow upward into the upper half because of its natural buoyancy. Therefore, it does not appear to be feasible to purge the MLI system alone with gaseous

helium if the larger surrounding volume is not also purged with helium.

Test 2E-2 was essentially a repeat of Test 2D-2 with the vacuum chamber gaseous helium purge rate reduced to 1.13 volumes per hour (table I). During this test, one additional round of gas samples was taken very shortly after the start of the test. The test results (shown in fig. 27) indicated no significant differences when compared to Test 2D-2. The variation in the vacuum chamber purge rate from 2.36 to 1.13 volumes per hour was, therefore, not significant.

Tests 4A and 4B were essentially repeats of Test 2D-2 with a subsequent ambient temperature vacuum chamber pumpdown and repressurization sequence added to the end of each purge test. Only two rounds of gas samples were withdrawn from the insulation system in each test. The measured gaseous nitrogen concentrations for the butt joints were slightly higher than those obtained for Test 2D-2 (figs. 27(a) to (d)), while the concentrations measured within the MLI panels were about the same as those obtained for Test 2D-2. The vacuum chamber pressure histories during the pumpdown and repressurization cycles are shown in figures 29 and 30, respectively. One purpose of these tests were to checkout the pumpdown and repressurization capabilities of the test facility. A second purpose was to determine if the pressure cycling present during the pumpdown and repressurization cycles would damage the MLI system structurally so that the subsequent space-hold thermal performance of the insulation system might be affected. For Test 4B, the vacuum chamber was repressurized with gaseous nitrogen while the MLI system was repressurized with gaseous helium (table I). The volumetric flow rate ratio, $\dot{\nu}_{MLI}/\dot{\nu}_{VC}$, where $\dot{\nu}_{MLI}$ is the volumetric flow rate for MLI system in MLI system volumes per hour and $\dot{\nu}_{VC}$ is the volumetric flow rate for vacuum chamber in vacuum chamber volumes per hour was calculated to be approximately equal to 2 for the repressurization sequence. This volumetric flow rate would, hopefully, provide for a positive flow of helium purge gas out from within the MLI system. A third purpose of Test 4B, then, was to determine if the MLI system helium purge could adequately prevent the gaseous nitrogen in the vacuum chamber from entering the MLI system. At the end of the repressurization sequence, however, gas samples obtained from within the MLI system indicated that the gaseous nitrogen concentration varied from 89 percent in the upper conical MLI panel to 98 percent in the lower conical MLI panel. Again, this purge (repressurization) technique was not successful in excluding the nitrogen gas from the MLI system. Therefore, this technique is probably unsuitable for a Space Tug-type vehicle in the Cargo Bay of the Space Shuttle Orbiter where it would be desirable to prevent atmospheric air, water vapor, and so forth, from contaminating the MLI system.

Tests 6A and 6B were essentially repeats of Test 2D-2 with an attempt to heat both the purge gas and MLI system components to a temperature of 344 K (620° R). The reason for doing this was to determine the effect of subjecting the MLI system to

a high temperature environment on its subsequent space-hold thermal performance in the event that the high temperature purge might later prove to be effective in removing water vapor from within the MLI panels. Increasing the MLI panel temperatures to 344 K (620° R) was attempted in Test 6A by utilizing just the purge gas heater (fig. 18) which heated only the gaseous helium purge to the MLI system; the shroud temperature was maintained at 300 K (540° R). However, the heat sink capacity of both the test tank and the MLI system was too large for the heat contained in the gaseous helium purge flow, and the MLI system was heated only a few degrees above the ambient temperature. During Test 6B, both the purge gas heater and the shroud heaters were set at 350 K (630° R), and the insulation system reached a temperature of approximately 344 K (620° R) or greater during the last 1½ hours of the purge test. The purge test results for both Tests 6A and 6B (fig. 27) were approximately the same as had been achieved in the previous tests (i.e., Tests 2D-2, 2E-2, 4A, and 4B) indicating that there was no significant effect of the higher temperatures on the gaseous nitrogen concentrations measured within the MLI system. It should be noted that the calculated value of the diffusion coefficient would theoretically be approximately 23 percent greater when the temperature is increased from 300 to 344 K (540° to 620° R) (ref. 13).

The 12 differential pressure transducers installed in the gas sampling system (fig. 20) to measure the pressure differentials from points within the MLI system to the ambient vacuum chamber pressure were monitored from time to time during the gaseous helium purge tests. No measurable differential pressures were ever noted during the purge tests with the 0 to 1.4×10^{3} newtons per square meter differential pressure (0 to 0.2 psid) range pressure transducers.

Additional Space-Hold Thermal Performance Tests

Additional space-hold (vacuum) thermal performance tests (Tests 3, 5, and 7) were conducted to determine if any of the purge, pumpdown, or repressurization test conditions to which the MLI system had been subjected had degraded the MLI thermal performance. The test results (table I) indicated that, overall, the heat input attributed to the MLI had varied less than 10 percent for all four of the tests and that no significant thermal degradation had occurred. The heat input, compared to the initial test (Test 1), had increased somewhat for Tests 3 and 5, but then decreased for Test 7. The heat input for Test 7 was 7.23 watts (24.7 Btu/hr) which was only 0.7 percent higher than for Test 1. Therefore, it was concluded that no structural or other damage affecting the thermal performance of the MLI system had occurred. No attempt was made to visually inspect the MLI system at the end of this first phase of the test program. Instead, the second phase of the overall test program (reported in ref. 14) was started immediately.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the gaseous helium purge characteristics of a multilayer insulation (MLI) system mounted on a spherical liquid hydrogen propellant tank. The propellant tank had a diameter of 1.39 meters (4.57 ft). The primary purpose of this investigation was to determine the time required to purge the condensible gaseous nitrogen initially contained within the insulation panels with the noncondensible helium purge gas by means of gas diffusion to obtain nitrogen gas concentrations of 1 percent or less. A second objective was to determine if any degradation of the space-hold (vacuum) thermal performance of the MLI system had occurred as a result of the purge tests or as a result of other pumpdown and repressurization tests conducted with the insulation system. All tests were conducted with the insulated test tank mounted within a cylindrical vacuum chamber.

The multilayer insulation consisted of two blankets; each blanket contained 15 double-aluminized Mylar (DAM) radiation shields alternated with 16 double silk net spacers. The radiation shields and silk net spacers of each blanket were enclosed between two laminated, aluminized Mylar/Dacron scrim cover sheets. The insulation system utilized six 60°-gore MLI panels on the sides of the test tank, one conical MLI panel on the top and one conical MLI panel on the bottom of the test tank in each blanket of insulation.

Gaseous nitrogen was initially contained within the MLI system and vacuum chamber at ambient temperature and pressure at the start of each purge test. Helium purge gas was introduced both underneath the MLI panels and into the vacuum chamber itself for all but one of the purge tests. For the remaining test, gaseous nitrogen, rather than gaseous helium, was introduced into the vacuum chamber. Insulation purge rates from 10 to 37 MLI system volumes per hour were used while the vacuum chamber purge rate was normally set at approximately 2.4 vacuum chamber volumes per hour. The multilayer insulation panels themselves were assumed to be purged of gaseous nitrogen primarily by means of gas diffusion.

The results obtained from this test program are summarized as follows:

1. For the initial gaseous helium purge tests (Tests 2B to 2D-1), the time required to achieve 1 percent gaseous nitrogen concentrations within the MLI system changed little when the MLI purge rate was increased from 10.1 to 20.2 MLI volumes per hour; however, there was a 30 to 40 percent decrease in the time required when the purge rate was further increased to 36.8 MLI volumes per hour. These inconsistencies may have been due to some slight shifting of the MLI panels during the conduct of the tests causing some variations in the width of the gaps at the butt joints between insulation panels. Overall, for all three tests, gaseous nitrogen concentrations of 1 percent were achieved within (1) the upper conical MLI panel within 74 minutes after

the start of the purge test, (2) the upper and lower halves of the MLI gore panels within 87 and 103 minutes, respectively, and (3) the lower conical MLI panel within 168 minutes. Overall, test results indicated that gaseous nitrogen concentrations well below 1 percent could be achieved everywhere within the MLI system.

2. Predictions of the gaseous nitrogen concentration with the MLI panels as a function of time were made using the Systems Improved Numerical Differencing Analyzer (SINDA) computer program. Purging of the gaseous nitrogen initially contained within the MLI panels with gaseous helium was assumed to occur by means of gas diffusion; the buoyancy of the helium purge gas in the initial gaseous nitrogen background was not accounted for. The predicted nitrogen concentrations agreed fairly well with the measured values for Test 2D-1 for the assumed diffusion coefficient of 5.30×10^{-3} square meter per minute (5.70×10^{-2} ft^2/min). The predicted nitrogen concentration as a function of time was somewhat greater than that observed experimentally within (1) the upper conical MLI panel throughout the purge test, and (2) the upper and lower halves of the MLI gore panel for approximately the first 80 minutes of the purge test. The differences between the predicted and measured gaseous nitrogen concentrations are attributed to the natural buoyancy of the helium purge gas in the gaseous nitrogen background aiding the gas diffusion process and, thereby, reducing the nitrogen concentration within the MLI panels early in the purge test at a faster rate than would have occurred otherwise. The predicted nitrogen concentration for the lower conical MLI panel provided the best agreement with the measured values.

3. Additional gaseous helium purge tests (Tests 2D-2 to 6B) at MLI purge rates of approximately 37 MLI volumes per hour indicated that the time required to purge the MLI panels to 1 percent gaseous nitrogen concentration were approximately 69 minutes for the upper conical MLI panel, 75 to 97 minutes for the upper and lower halves of the MLI gore panels, and 158 minutes for the lower conical MLI panel. These times were not significantly different from those mentioned previously for the lower MLI purge rates of 10.1 and 20.2 MLI volumes per hour. This may, again, have been due to some slight shifting of the MLI panels between tests 2D-1 and 2D-2 creating variations in the width of the gaps at the butt joints between insulation panels. The purge results for the additional tests having similar test conditions were all fairly consistent indicating that no further changes in the purge characteristics had taken place within the MLI system. Changes in the vacuum chamber purge rate from 2.4 to 1.1 chamber volumes per hour and purge temperatures from 300 to 344 K (540° to 620° R) did not significantly affect the time required to achieve 1 percent gaseous nitrogen concentration within the MLI system. Predictions of the gaseous nitrogen concentration within the MLI panels using the SINDA computer program showed better agreement with the experimental data than previously (Test 2D-1). Again, the predicted nitrogen concentration as a function of time was somewhat greater than that observed experimentally

within (1) the upper conical MLI panel throughout the purge test, and (2) the upper and lower halves of the MLI gore panel for the first 70 to 80 minutes of the purge test. The predicted nitrogen concentration for the lower conical MLI panel again agreed reasonably well with the measured values.

4. One purge test conducted with the vacuum chamber purged with gaseous nitrogen rather than gaseous helium indicated that nitrogen concentrations within the MLI system could not be reduced to less than 30 percent. Therefore, it does not appear feasible to purge the MLI system alone with gaseous helium if the larger surrounding volume is not also purged with helium.

5. Four space-hold (vacuum) thermal performance tests conducted periodically during the purge test program indicated that the heat input attributed to the MLI system had not changed significantly (<10 percent) for any of the tests. The final measured heat input was 7.23 watts (24.7 Btu/hr) which was only 0.7 percent higher than the 7.18-watt (24.5-Btu/hr) heat input obtained for the initial baseline thermal performance test (Test 1). This indicated that neither the ambient temperature purge, pumpdown, and repressurization tests nor the 344 K (620° R) temperature purge test had degraded the thermal performance of the MLI system.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 9, 1977,
506-21.

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16. Smith, James P.: Systems Improved Numerical Differencing Analyzer (SINDA): User's Manual. (TRW-14690-H001-RO-00, TRW Systems Group; NASA Contract NAS9-10435.) NASA CR-134271, 1971.

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TABLE I. - TEST SEQUENCE AND PURGE TEST CONDITIONS

Test	Type test	Ground-hold purge conditions							Space-hold MLI thermal performance, W	Repressurization		
		MLI			Chamber					Purge gas		Time required, min
		GHe purge rate		Heater temperature, K	Gas	Purge rate		Shroud temperature, K		MLI	Chamber	
		kg/hr	vol/hr			k_g/hr	vol/hr					
1	SHTP[a]	----	----	---	----	----	----	300	7.18	----	----	--
2A	Purge	(b)	(b)	299	GHe	(b)	(b)	300	----	----	----	--
2B	↓	0.30	10.1	↓	↓	2.13	2.37	↓	----	----	----	--
2C		.60	20.2			2.15	2.39		----	----	----	--
2D-1		1.10	36.8			2.14	2.35		----	----	----	--
2D-2		1.10	36.8		↓	2.15	2.36		----	----	----	--
2E-1		1.10	36.6		GN_2	7.23	1.13		----	----	----	--
2E-2		1.10	36.8		GHe	1.03	1.13		----	----	----	--
3	SHTP[a]	----	----	---	----	----	----	300	7.33	----	----	--
4A	Purge	1.10	36.7	299	GHe	2.14	2.35	301	----	GHe	GHe	38
4B	Purge	1.10	37.1	299	GHe	2.13	2.37	301	----	GHe	GN_2	49
5	SHTP[a]	----	----	---	----	----	----	300	7.86	----	----	--
6A	Purge	0.97	32.4	358	GHe	2.18	2.38	300	----	----	----	--
6B	Purge	.96	36.1	359	GHe	1.84	2.38	352	----	----	----	--
7	SHTP[a]	----	----	---	----	----	----	300	7.23	----	----	--

[a]Space-hold thermal performance.

[b]Leakage of purge gas at lid of vacuum chamber precluded satisfactory test.

Figure 1. - Test tank.

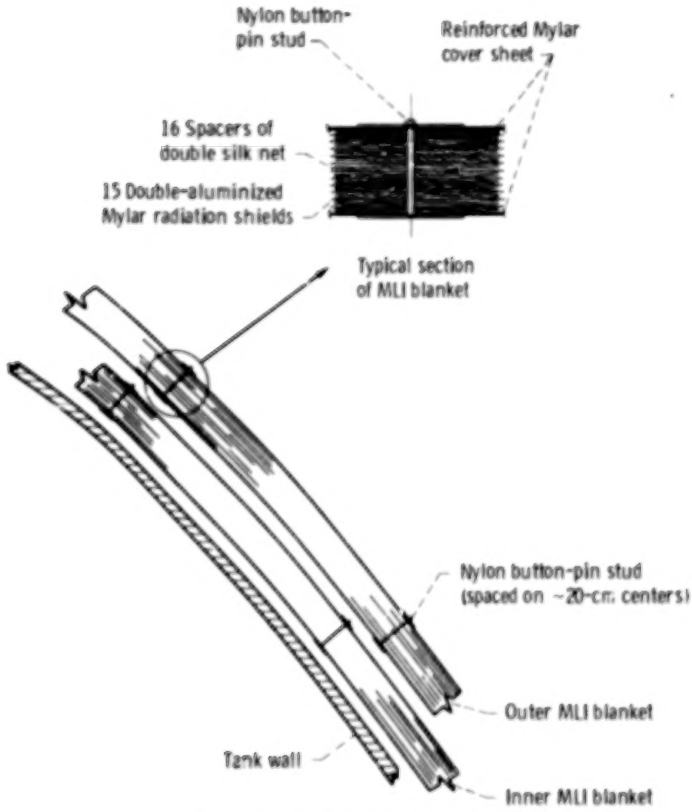
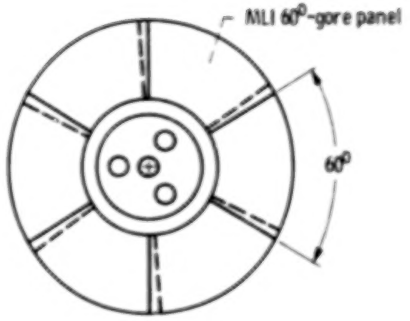
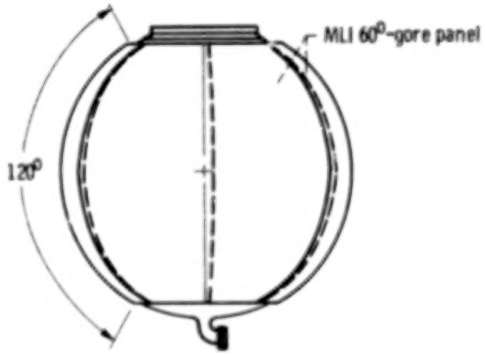

Nylon button-pin stud
Reinforced Mylar cover sheet
16 Spacers of double silk net
15 Double-aluminized Mylar radiation shields
Typical section of MLI blanket
Nylon button-pin stud (spaced on ~20-cm centers)
Outer MLI blanket
Tank wall
Inner MLI blanket

Figure 2. - Basic MLI blanket concept.

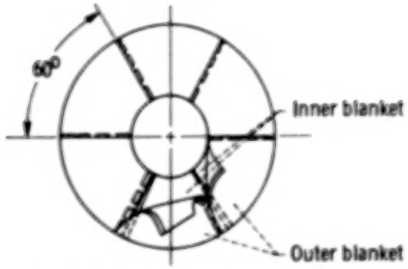


(a) Top view.

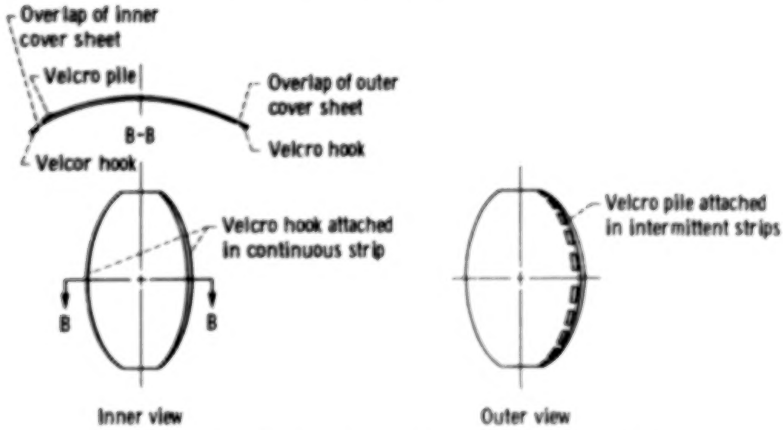


(b) Side view.

Figure 3. - Basic MLI 60°-gore panels for sides of test tank.

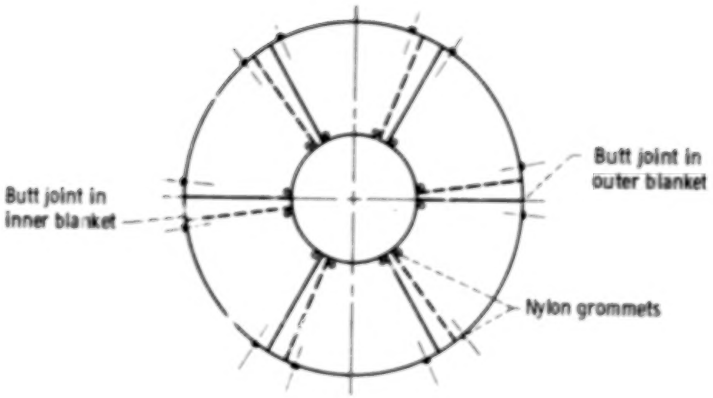


(a) Top view of tank with gore panels.

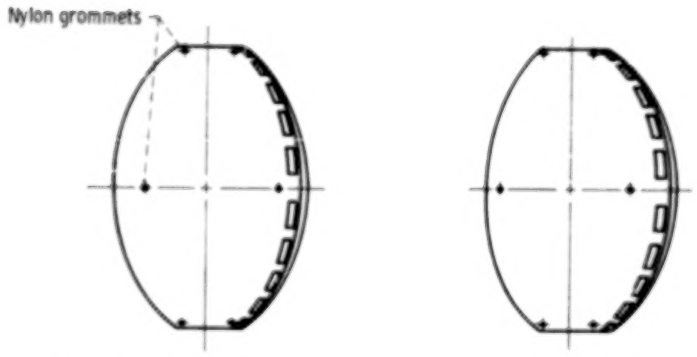


(b) Location of Velcro fastener on inner and outer cover sheets of MLI 60°-gore panels.

Figure 4. - Location of Velcro fastener used to install MLI gore panels on test tank.

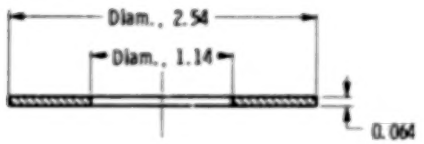


(a) Top view of tank showing grommet locations.

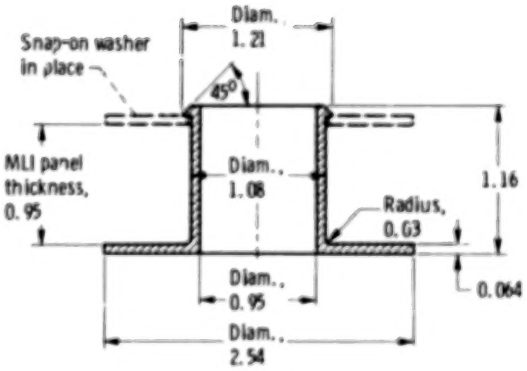


(b) Grommet locations on inner and outer MLI gore panels.

Figure 5. - Grommet locations on MLI gore panels.



(a) Snap-on washer.



(b) Grommet.

Figure 6. - Nylon grommet. (All dimensions are in cm.)

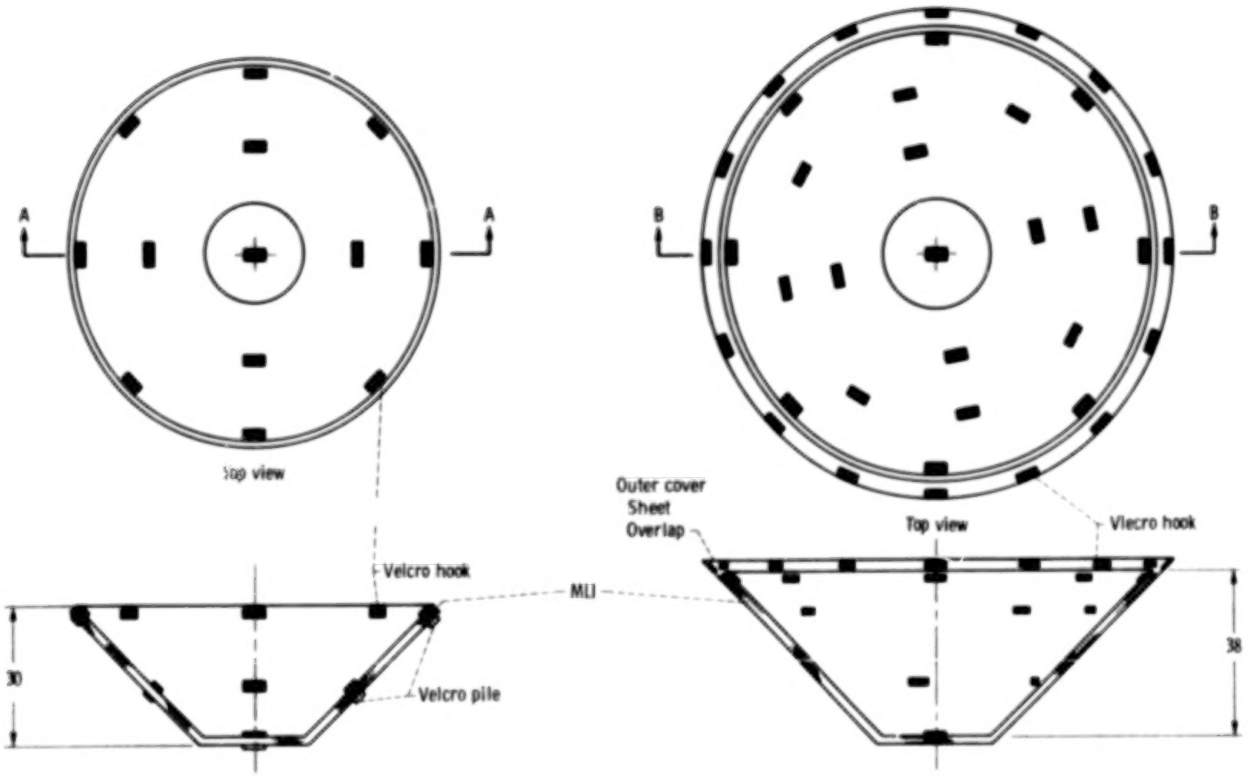


Figure 7. - General location of Velcro fastener on conical MLI panels at bottom of test tank. (All dimensions are in cm.)

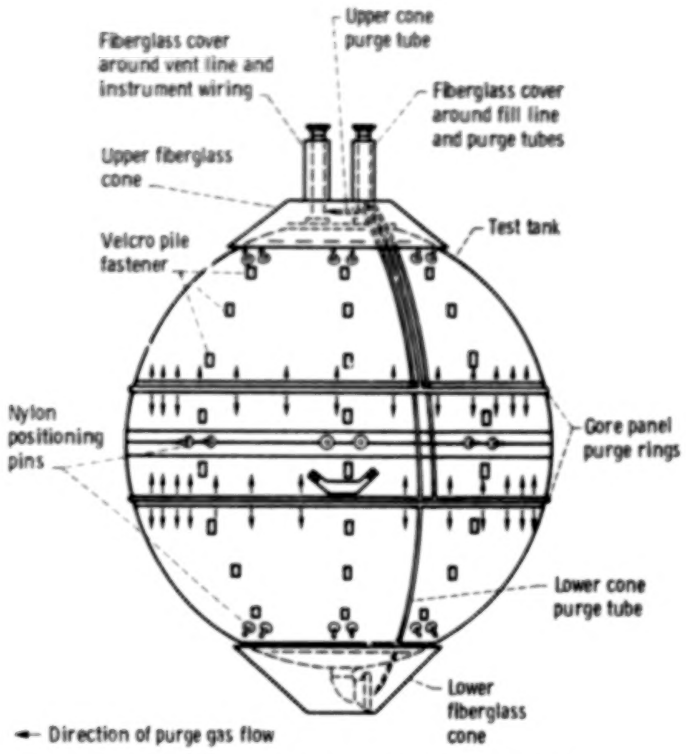
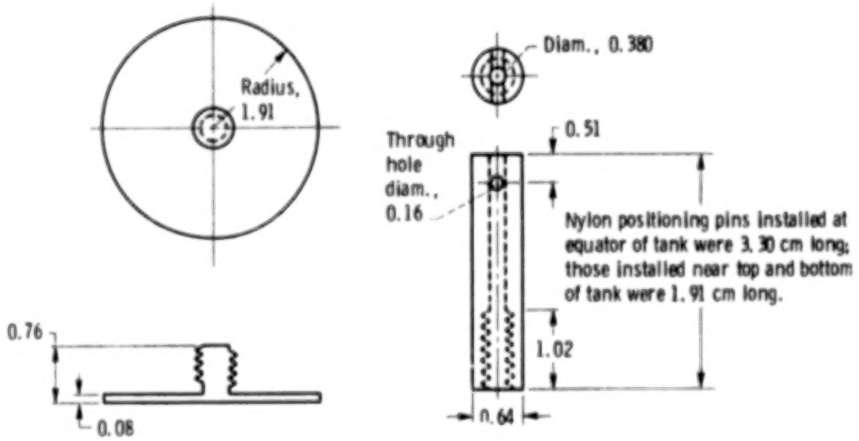

Upper cone purge tube
Fiberglass cover around vent line and instrument wiring
Fiberglass cover around fill line and purge tubes
Upper fiberglass cone
Test tank
Velcro pile fastener
Nylon positioning pins
Gore panel purge rings
Lower cone purge tube
Lower fiberglass cone
Direction of purge gas flow

Figure 8. - Test tank showing general location of purge tubing, nylon positioning pins, fiberglass cones, and Velcro pile fastener.


Radius, 1.91
0.76
0.08
Diam., 0.380
0.51
Through hole diam., 0.16
Nylon positioning pins installed at equator of tank were 3.30 cm long; those installed near top and bottom of tank were 1.91 cm long.
1.02
0.64

(a) Nylon positioning pin base.

(b) Nylon positioning pin stud.

Figure 9. - Nylon positioning pin. (All dimensions are in cm.)

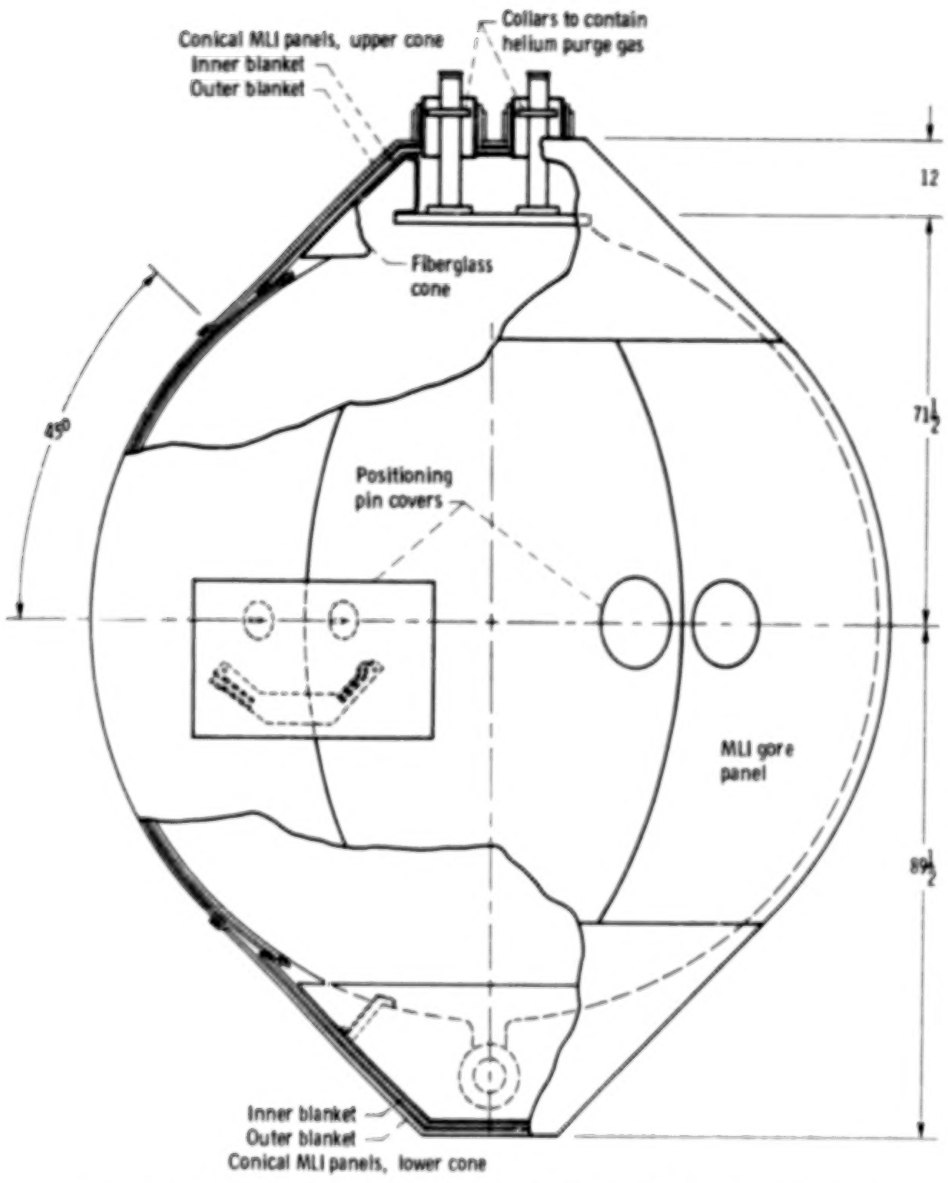


Figure 10. - Schematic of multilayer insulation system assembly. (All dimensions are in cm.)

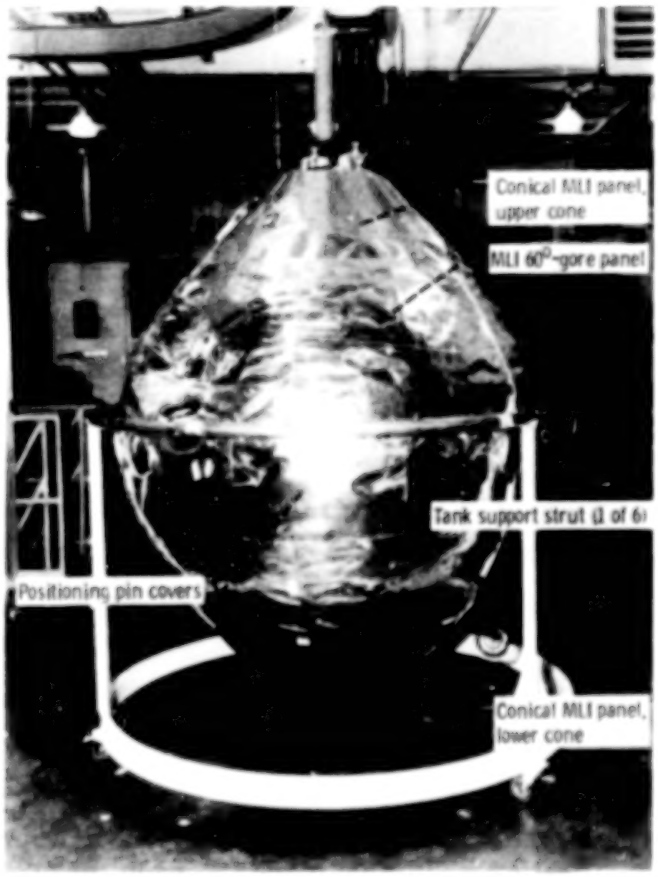

Conical MLI panel, upper cone
MLI 60°-gore panel
Tank support strut (1 of 6)
Positioning pin covers
Conical MLI panel, lower cone

Figure 11. - Multilayer insulation system installed on test tank.

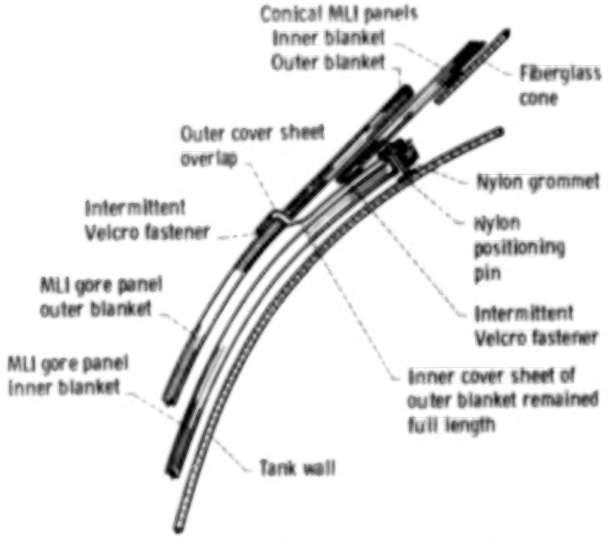


Figure 12. - Schematic of joints between MLI gore panels and conical MLI panels at top and bottom of tank.

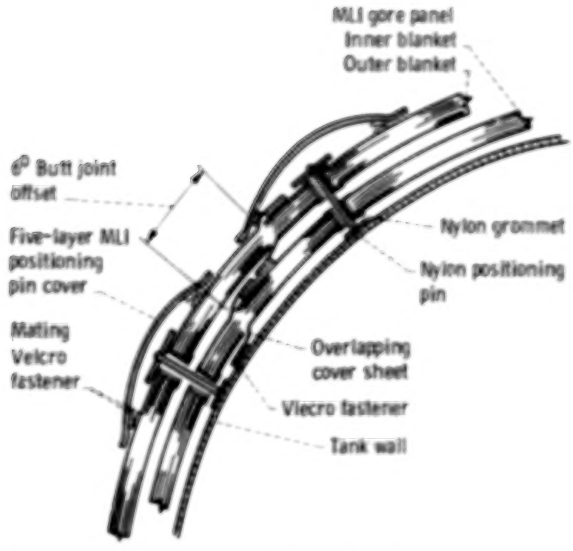


Figure 13. - Schematic of butt joint configuration between MLI gore panels showing overlapping cover sheets, shown in horizontal plane of tank equator with nylon positioning pins and five-layer MLI covers.

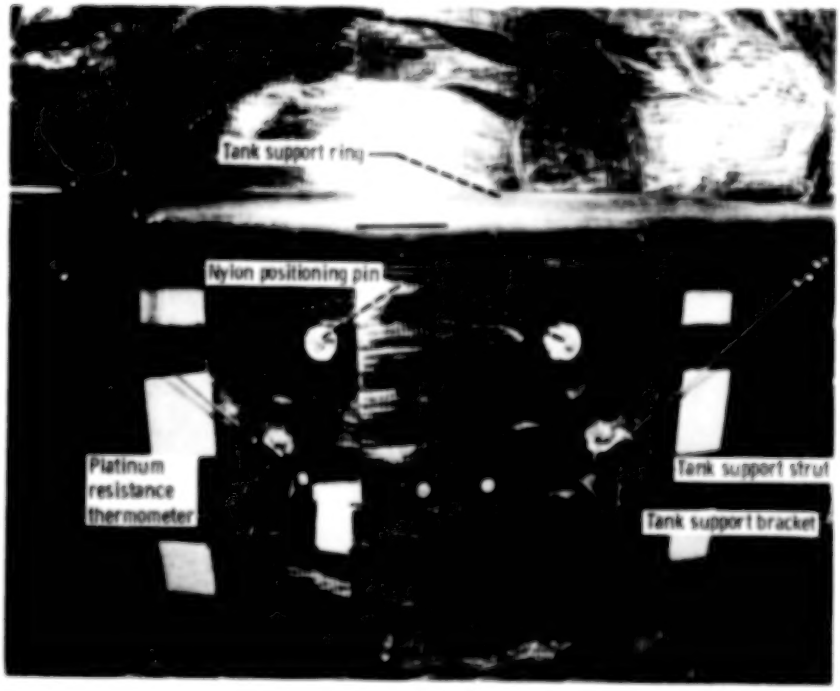
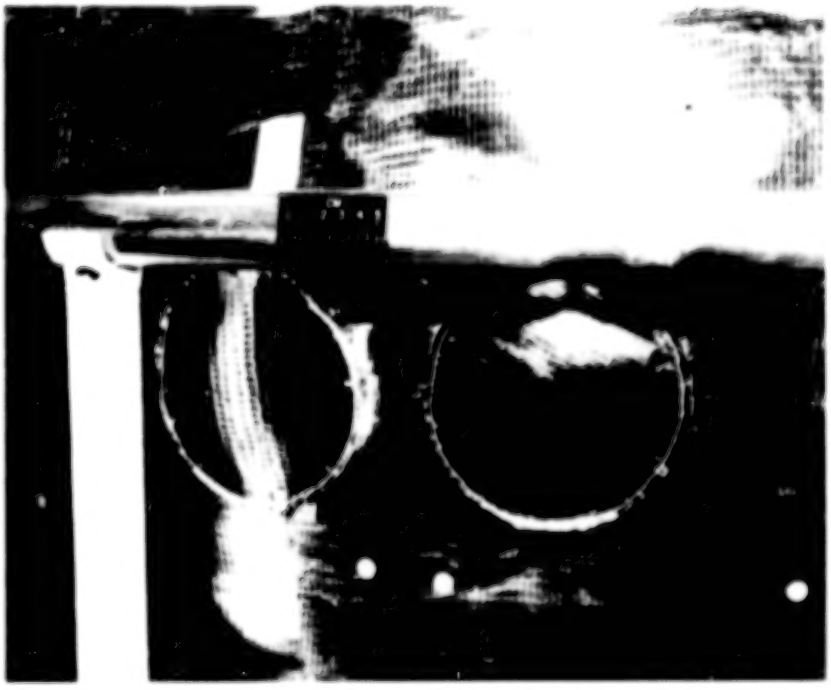


Figure 14. - Cutouts in MLI panels for tank support brackets.

(a) Vicinity of tank support brackets.



(b) For positioning pins only.

Figure 15. - Positioning pin covers.

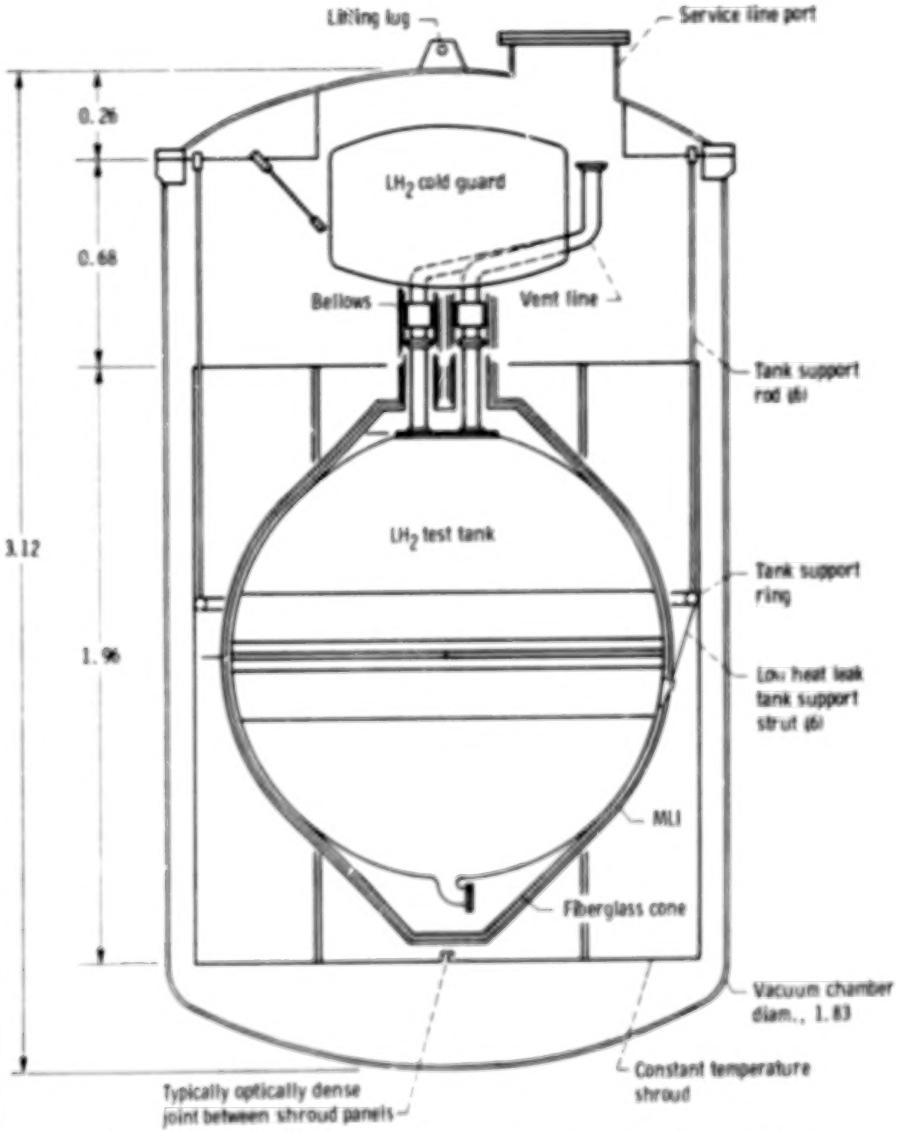


Figure 16. - Schematic showing insallation of insulated test tank in vacuum chamber. (All dimensions are in m.)

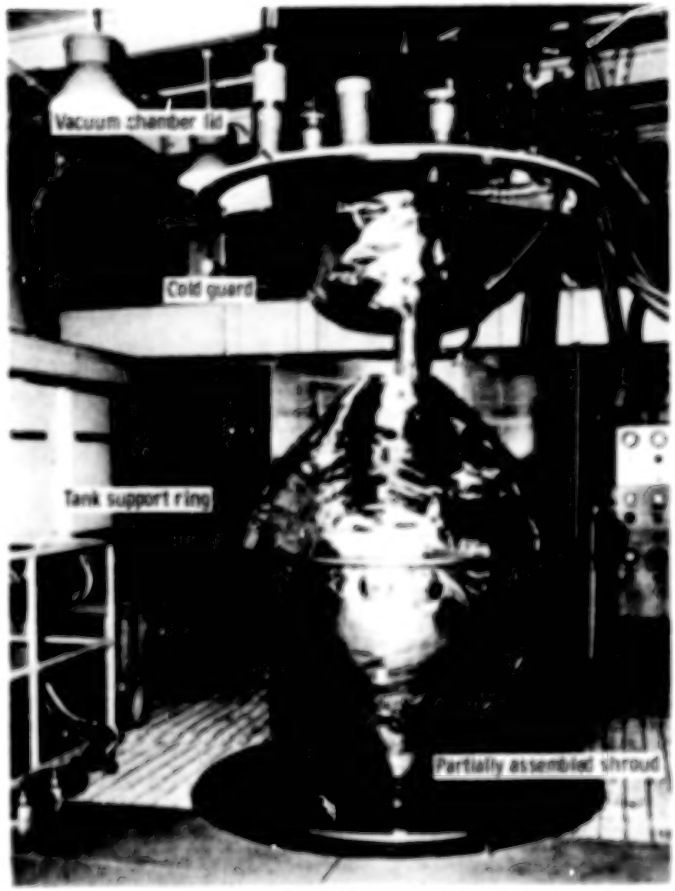


Figure 17. - Insulated test tank and cold guard.

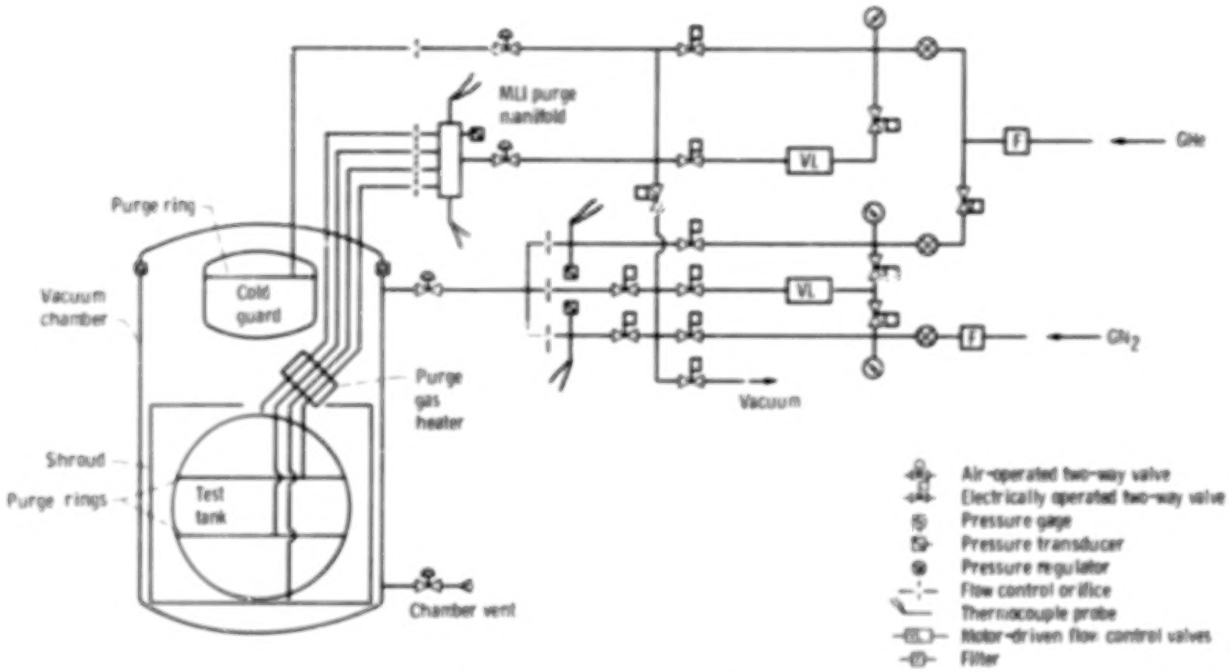
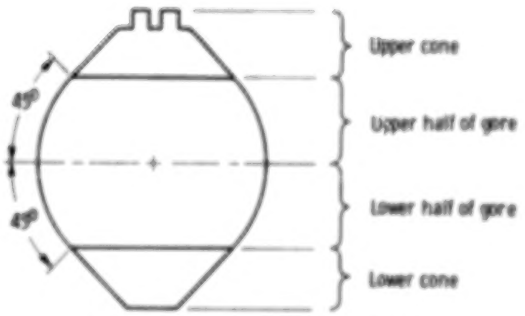


Figure 18. - Flow schematic for MLI and chamber purge system.



Four purge regions for insulation system

Purge region	Calculated volume		Calibrated volumetric flow	
	m^3	Percent of total	$\frac{d_o^2 C_d}{cm^2}$	Percent of total
Upper cone	0.0480	25.8	8.34×10^{-4}	27.3
Upper half of gore	.0433	23.3	6.84	22.4
Lower half of gore	.0433	23.3	6.86	22.5
Lower cone	.0515	27.7	8.47	27.8
Total	0.1861	100.1		100.0

d_o = orifice diameter, cm.
C_d = discharge coefficient for choked flow.

Figure 19. - Purge regions and flow distribution for multilayer insulation system.

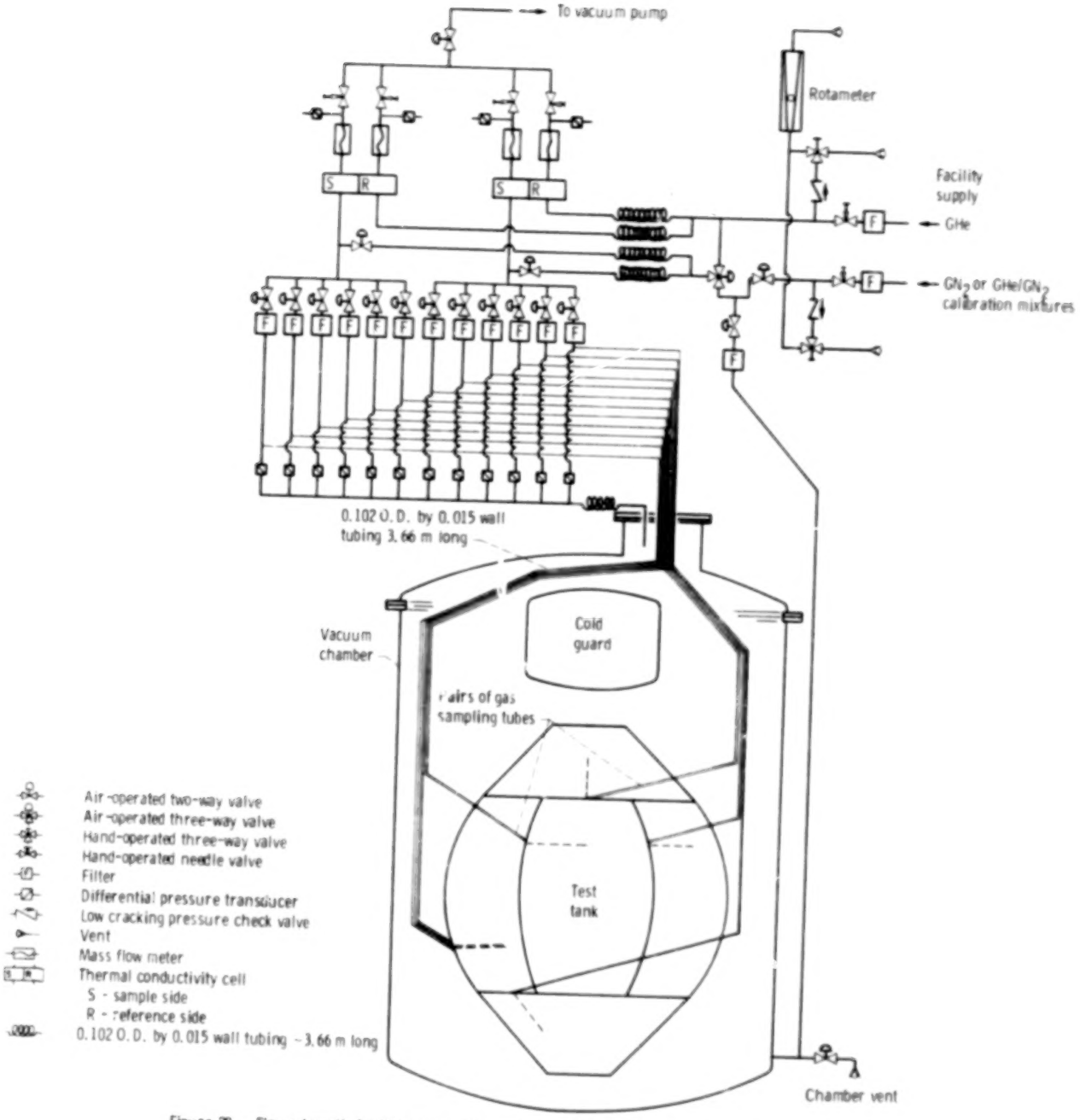
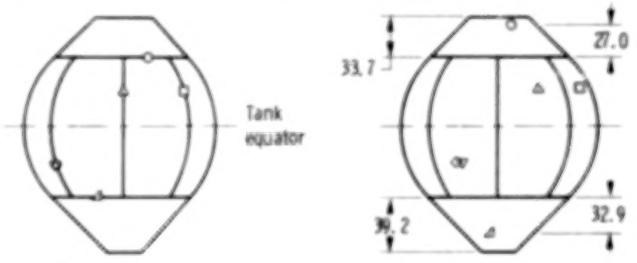


Figure 20. - Flow schematic for MLI gas sampling system. (All dimensions in cm unless otherwise noted.)

Sampling tube pair	Symbol	Butt joint location		MLI panel location		
		MLI blanket	Relative to tank equator	MLI blanket	Relative to	
					Tank equator	Panel vertical centerline
1	○	Outer	45° above	Outer	----------	----------
2	△	Outer	22.5° above	Outer	22.5° above	On vertical centerline
3	□	Outer	22.5° above	Outer	22.5° above	On vertical centerline
4	▽	Inner	22.5° below	Inner	22.5° below	On vertical centerline
5	◇	Outer	22.5° below	Outer	22.5° below	On vertical centerline
6	◁	Outer	45° below	Outer	----------	----------



(a) Butt joint locations. (b) MLI panel locations.

Figure 21. - Location of sampling tubes where gas samples from within MLI system were obtained. (All dimensions are in cm unless noted otherwise.)

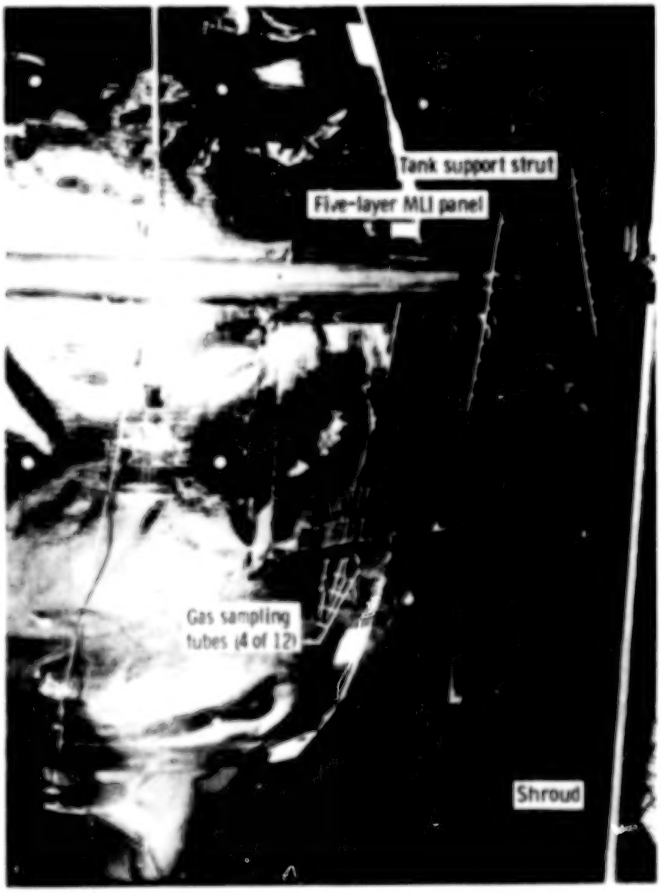
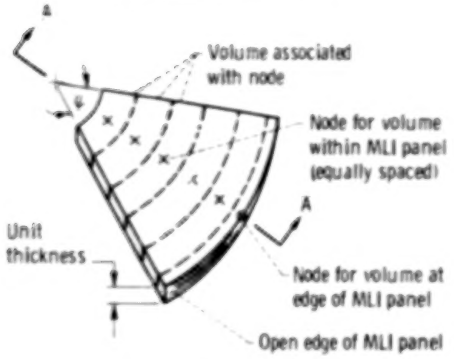
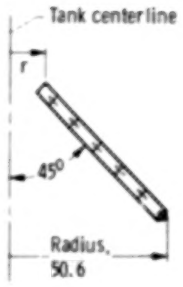


Figure 22. - Typical attachment of gas sampling tubes to MLI system.

Conical MLI panel	φ, deg	r, cm
Upper	87.1	17.5
Lower	85.2	10.8

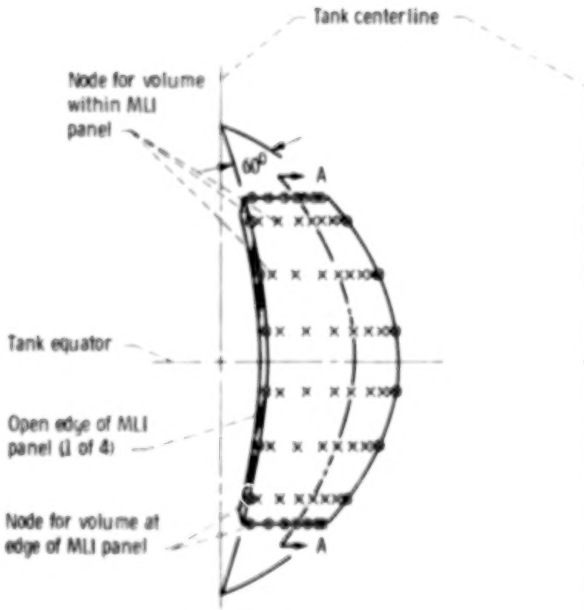

A
Volume associated with node
Node for volume within MLI panel (equally spaced)
Unit thickness
Node for volume at edge of MLI panel
Open edge of MLI panel

(a) Segment of conical MLI panel.

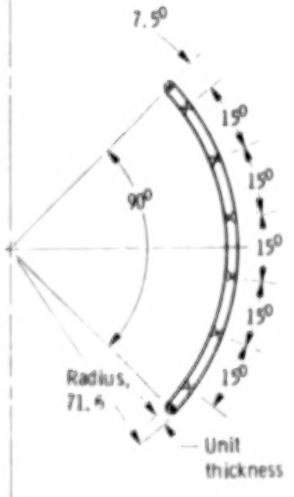


(b) Section A-A.

Figure 23. - Analytical model configuration for conical MLI panel of outer insulation blanket. (All dimensions are in cm.)



(a) 60°-gore panel.



(b) Section A-A.

Figure 24. - Analytical model configuration for MLI 60°-gore panel of outer insulation blanket. (All dimensions are in cm.)

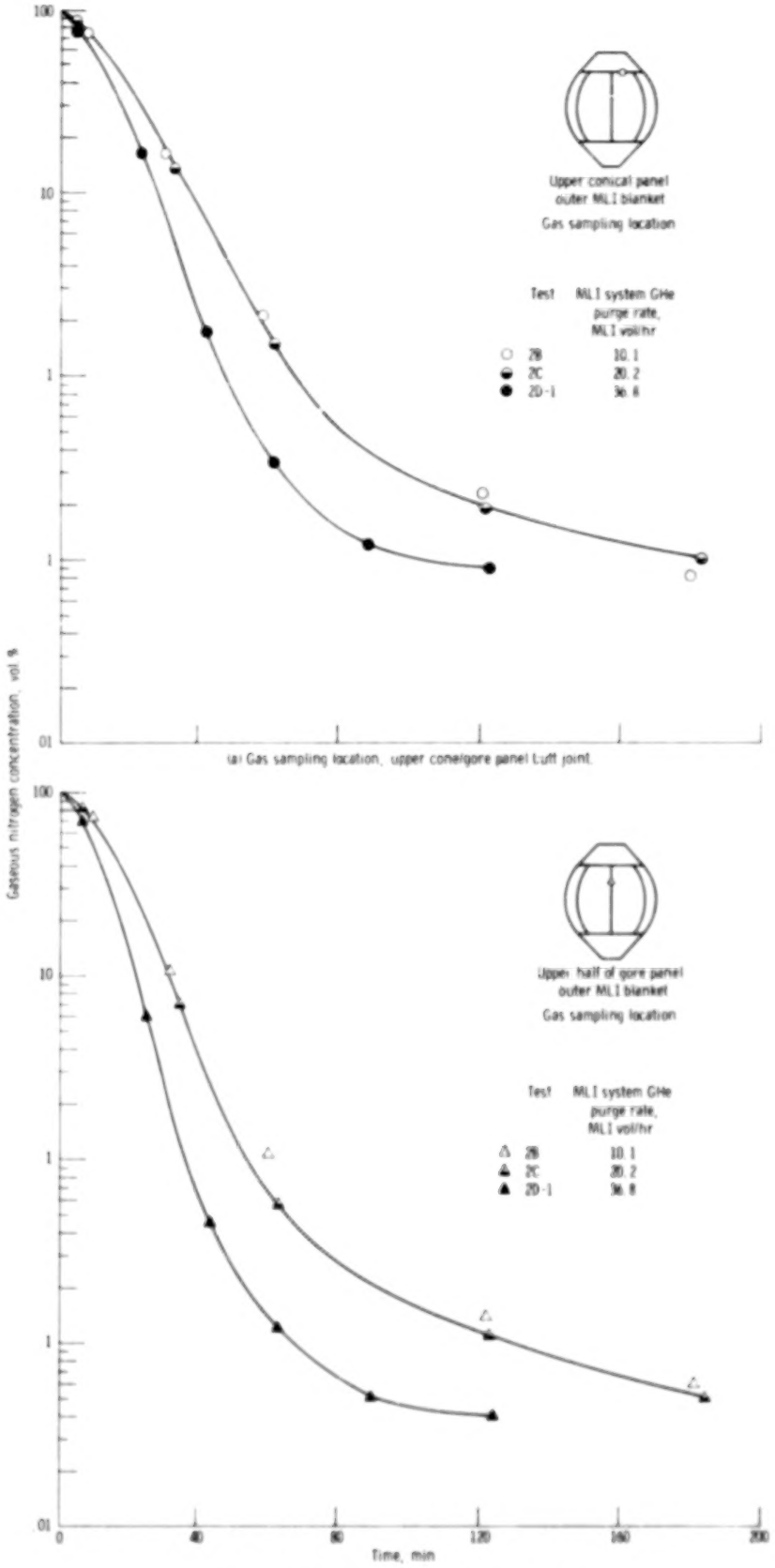
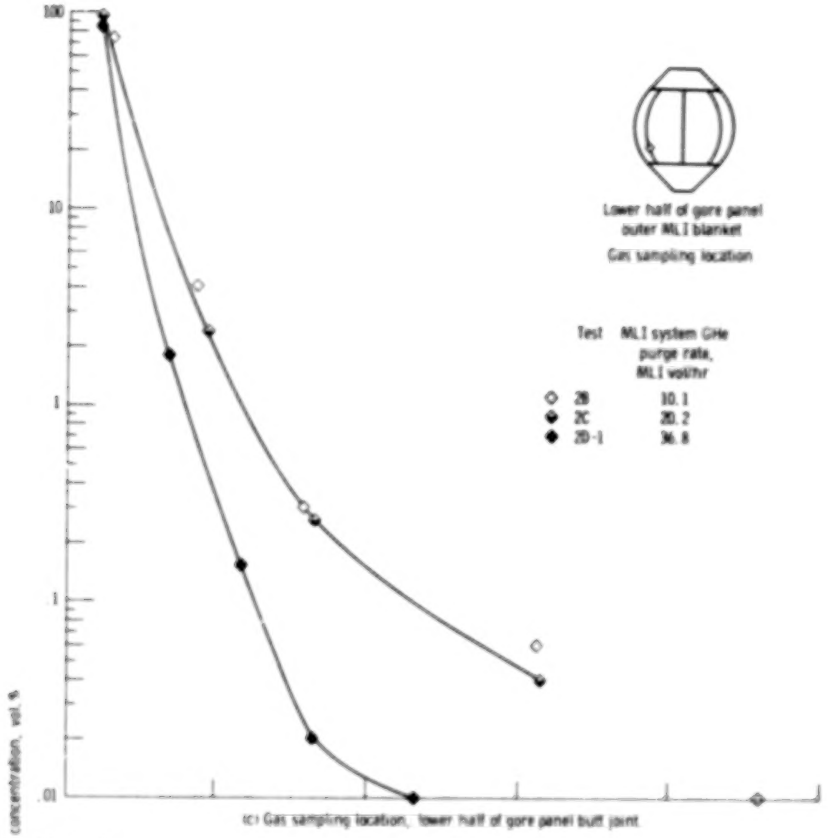
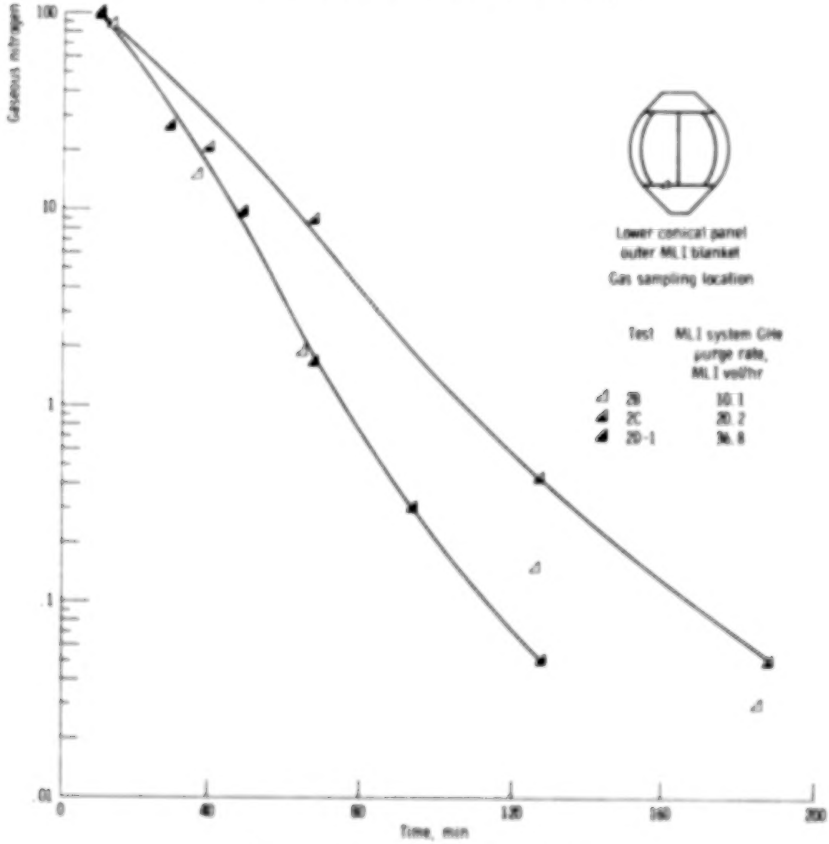


Figure 25 - Gaseous nitrogen concentration within MLI system. Tests 2B to 2D-1, vacuum chamber GHe purge rate, 2.4 volumes per hour.

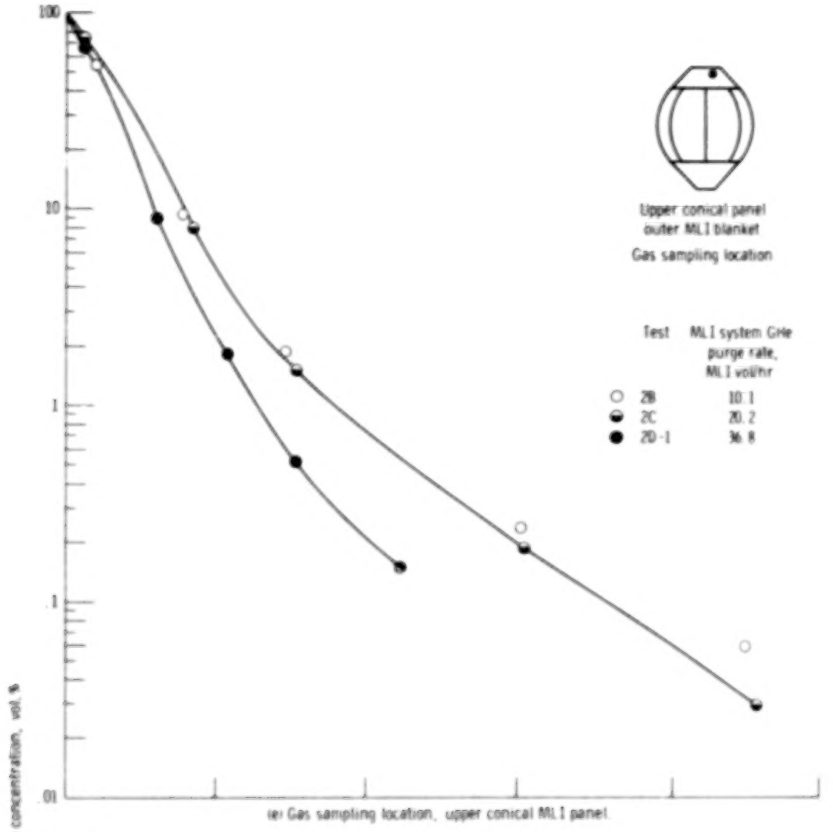


(c) Gas sampling location, lower half of gore panel butt joint.

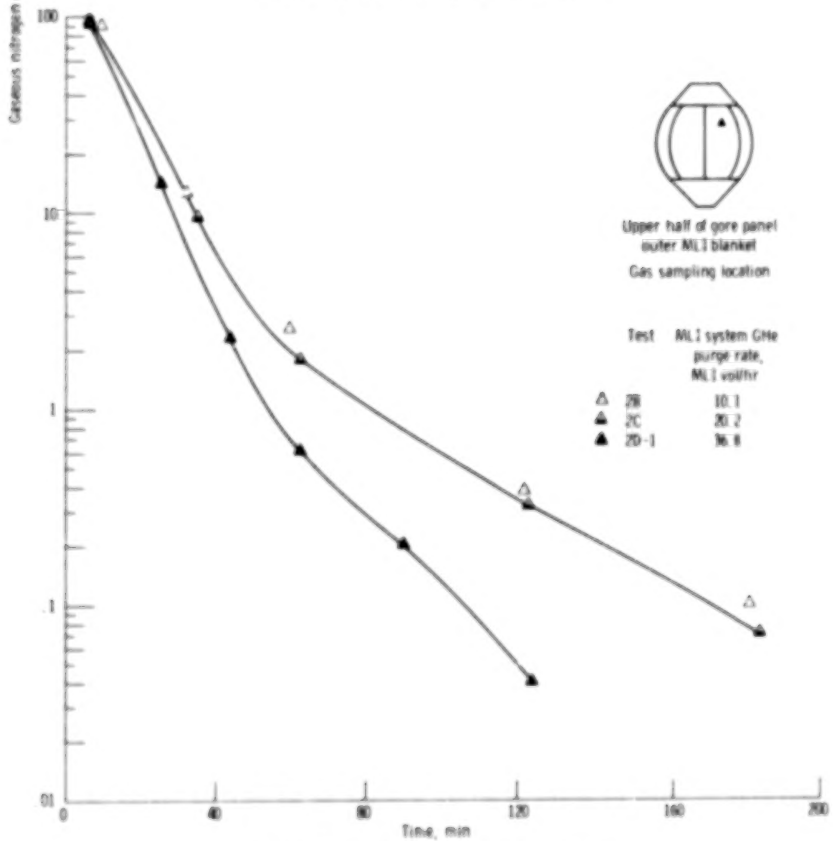


(d) Gas sampling location, lower cone/gore panel butt joint.

Figure 25. - Continued.

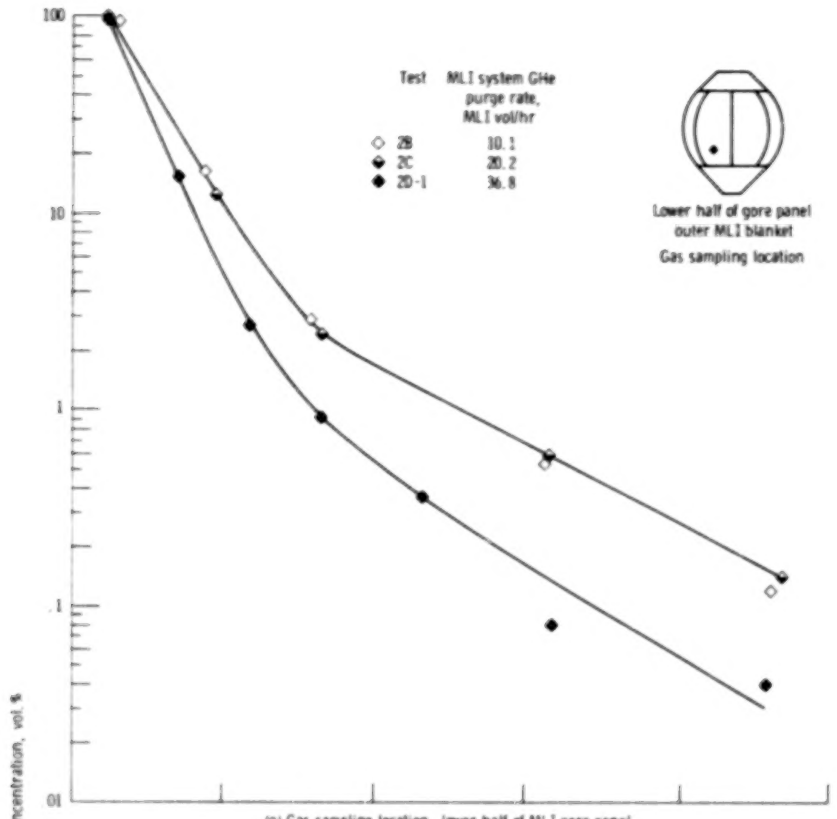


(e) Gas sampling location, upper conical MLI panel.

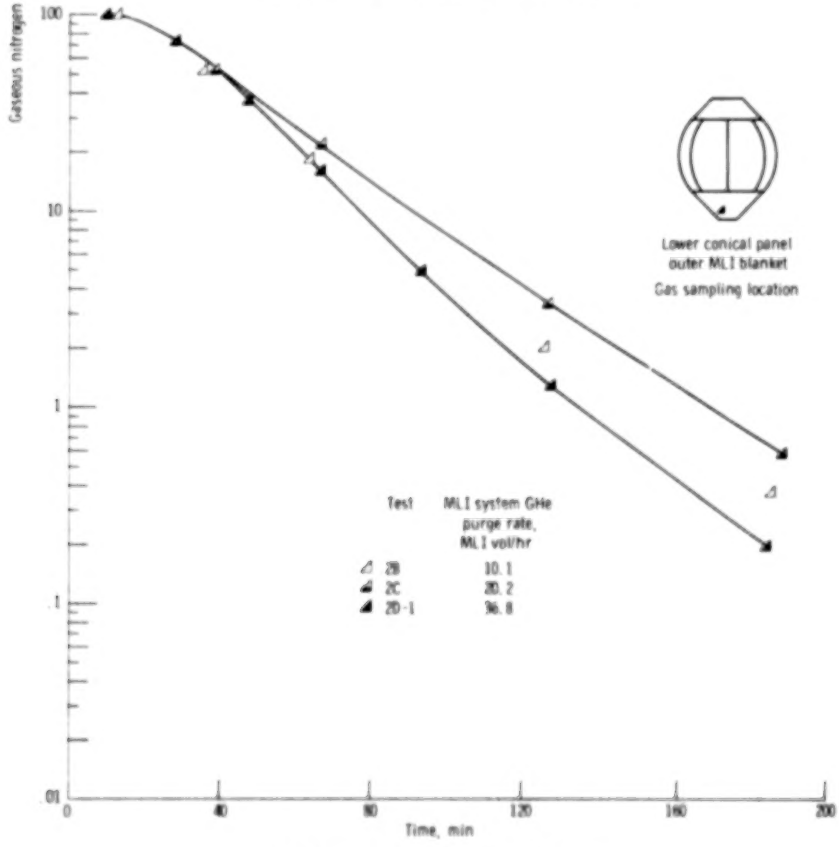


(f) Gas sampling location, upper half of MLI gore panel.

Figure 25 - Continued.



(g) Gas sampling location, lower half of MLI gore panel.



(h) Gas sampling location, lower conical MLI panel.

Figure 25. - Concluded.

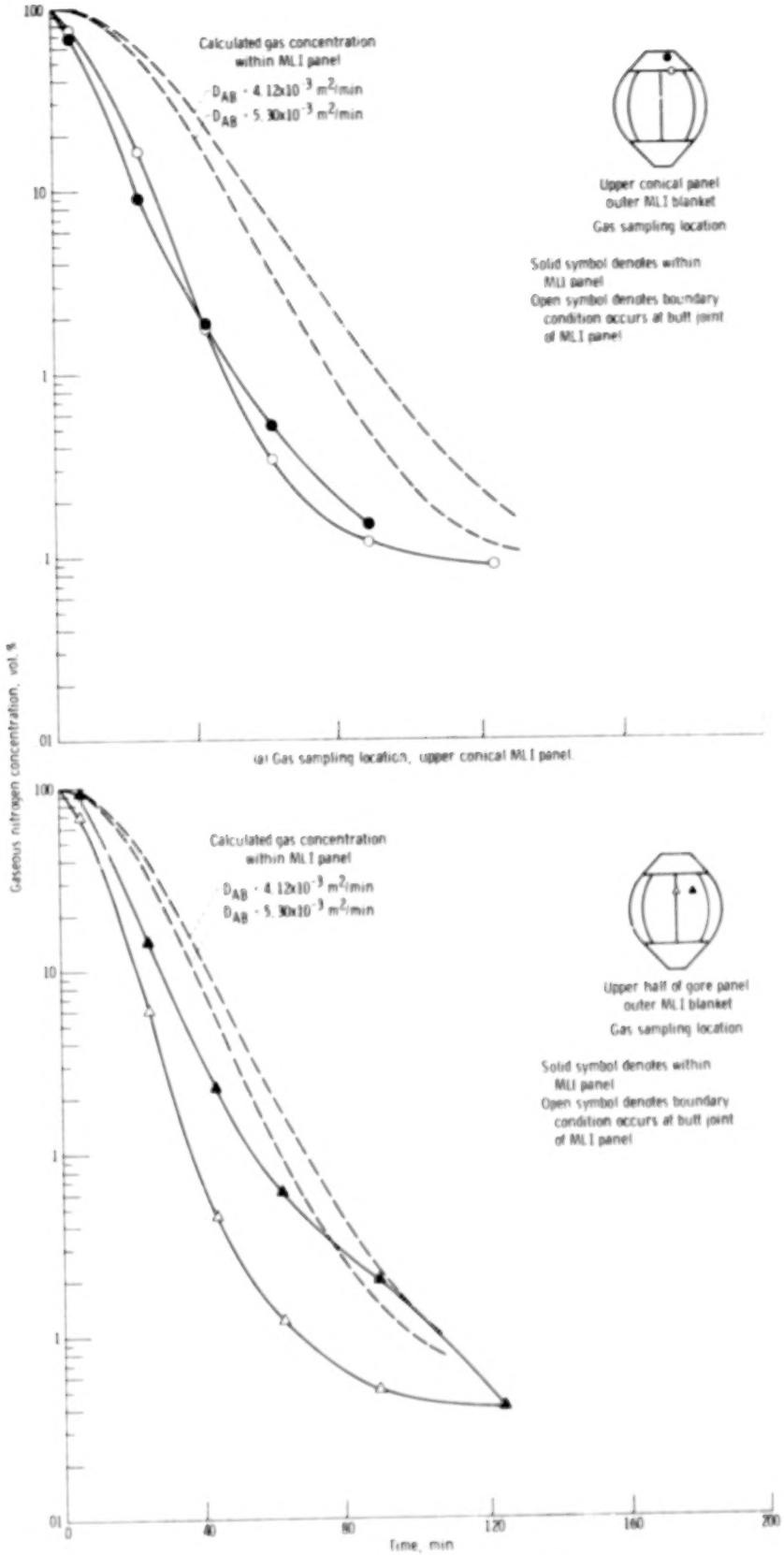
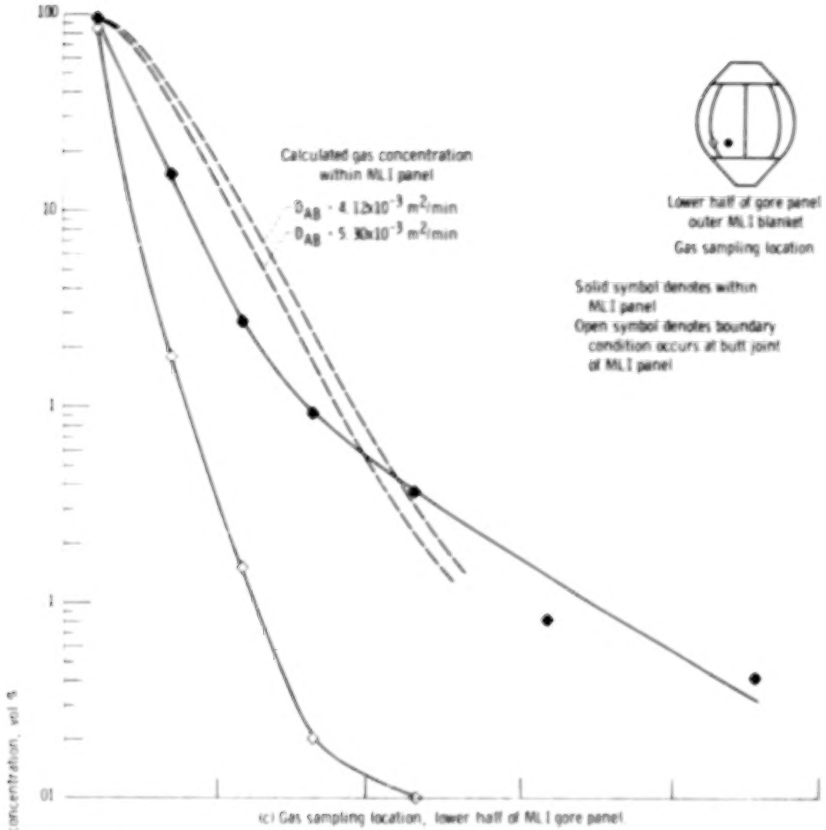
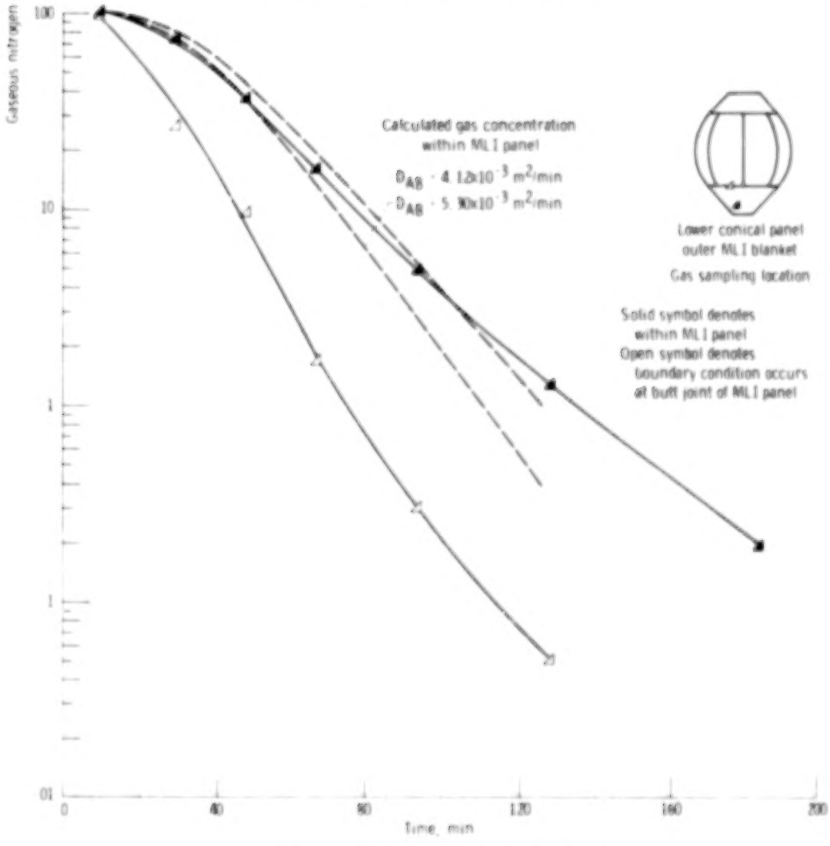


Figure 26. - Gaseous nitrogen concentration within MLI system. Test 2D-1, vacuum chamber GHe purge rate, 2.4 volumes per hour; MLI system GHe purge rate, 36.8 volumes per hour.


Calculated gas concentration within MLI panel
D_{AB} = 4.12x10^{-3} m^2/min
D_{AB} = 5.90x10^{-3} m^2/min
Lower half of gore panel outer MLI blanket
Gas sampling location
Solid symbol denotes within MLI panel
Open symbol denotes boundary condition occurs at butt joint of MLI panel
100
10
1
0.1

(c) Gas sampling location, lower half of MLI gore panel



(d) Gas sampling location, lower conical MLI panel.

Figure 28. - Concluded.

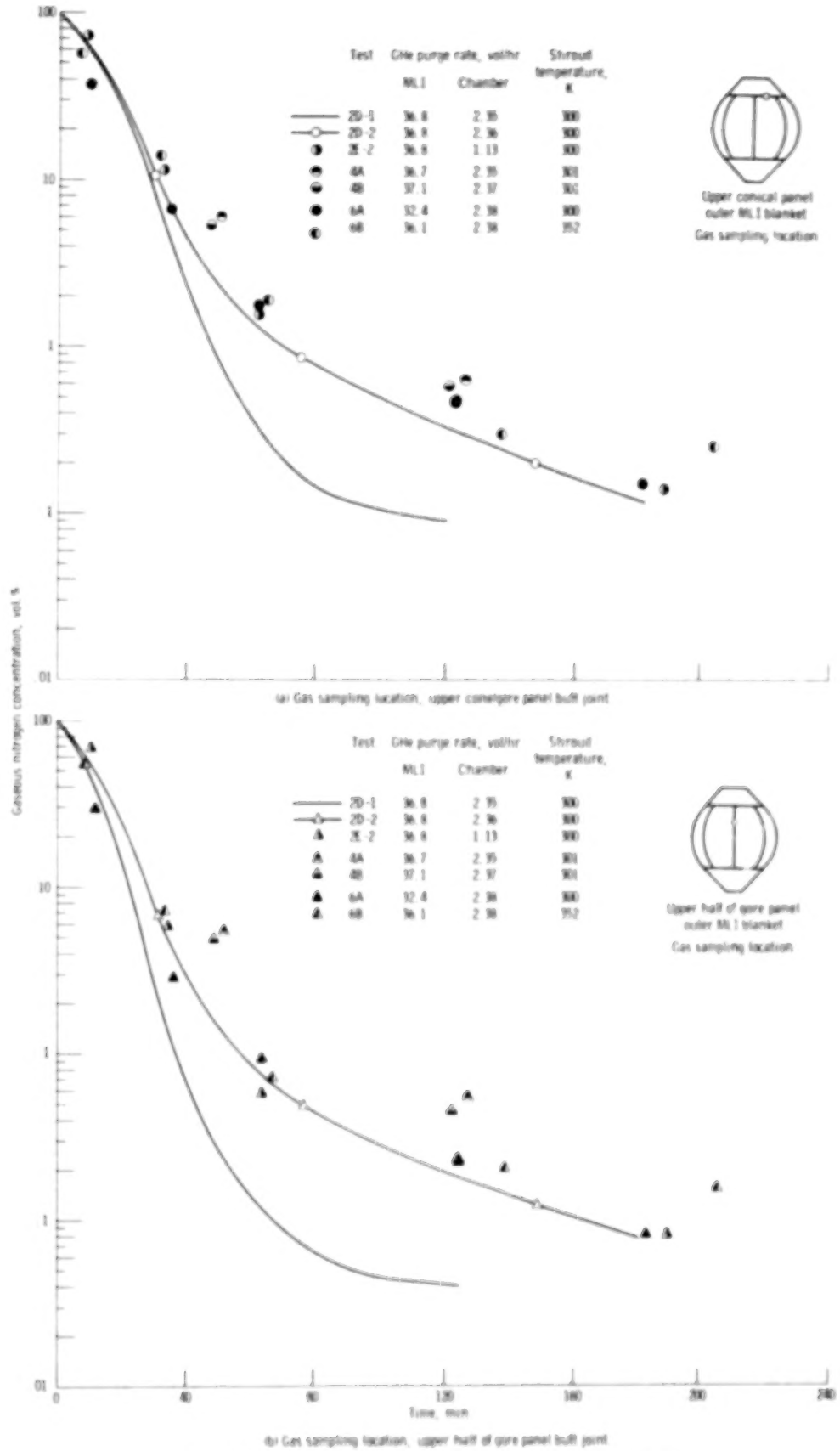
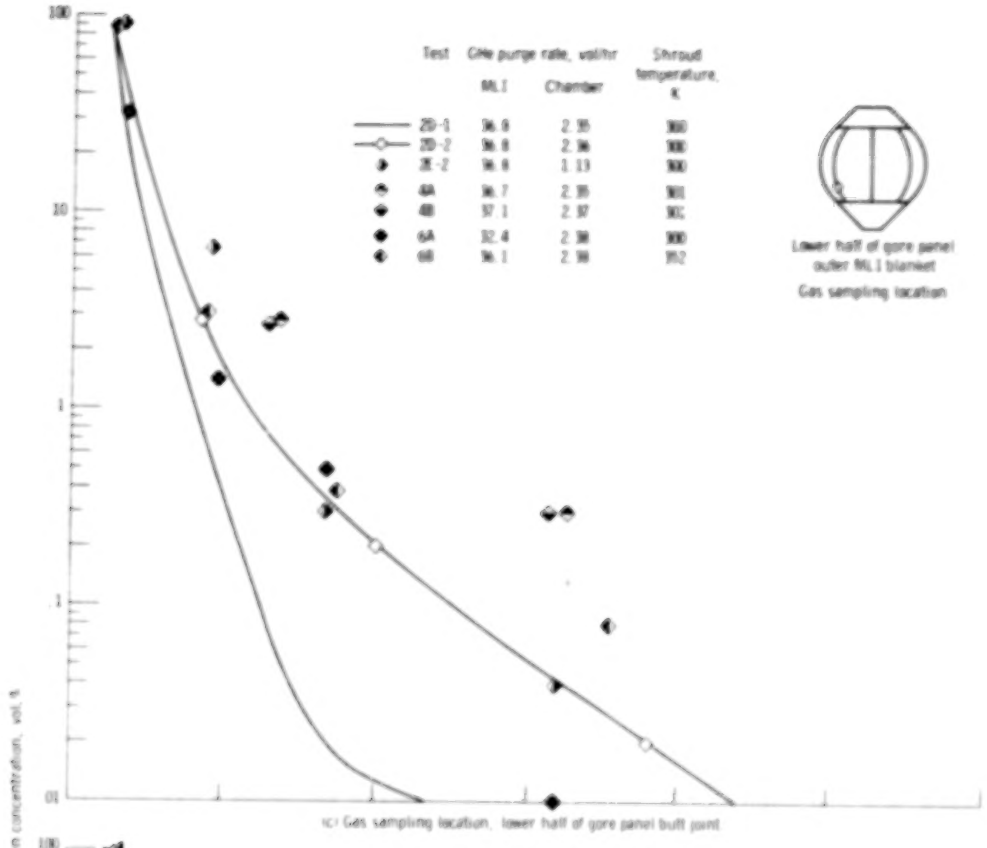
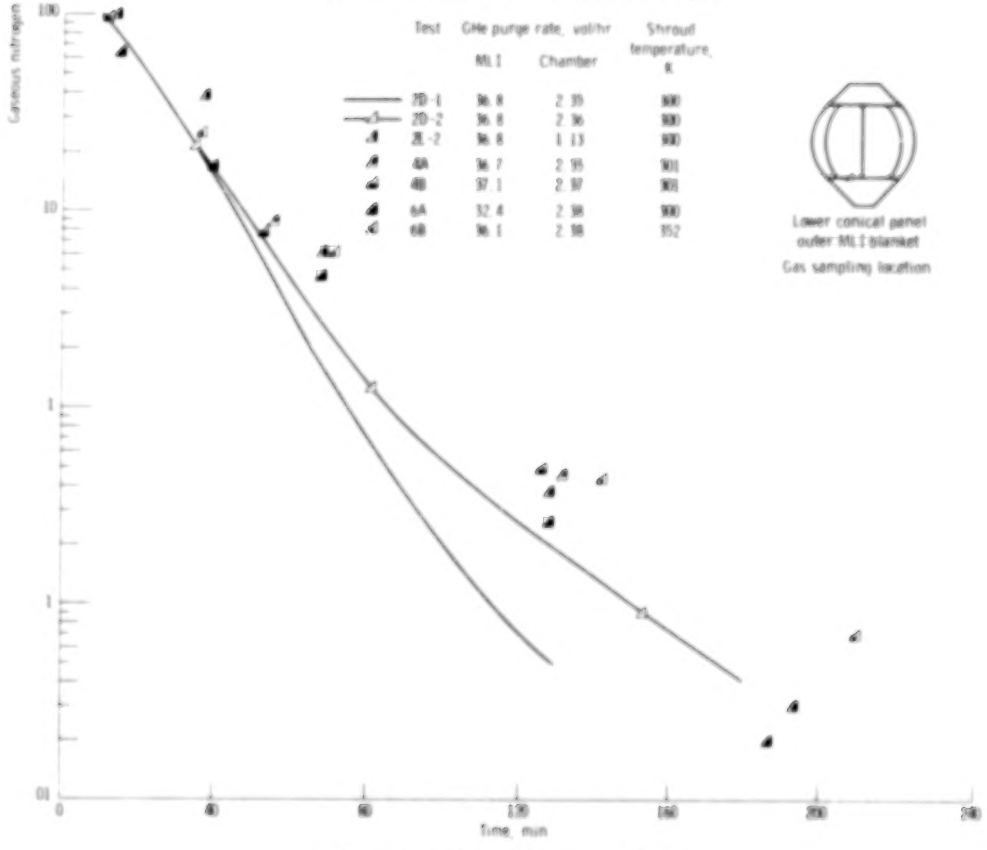


Figure 27 - Gaseous nitrogen concentration within MLI system. Purge tests 2D to 6B.



(c) Gas sampling location, lower half of gore panel butt joint



(d) Gas sampling location, lower cone/gore panel butt joint

Figure 27 - Continued.

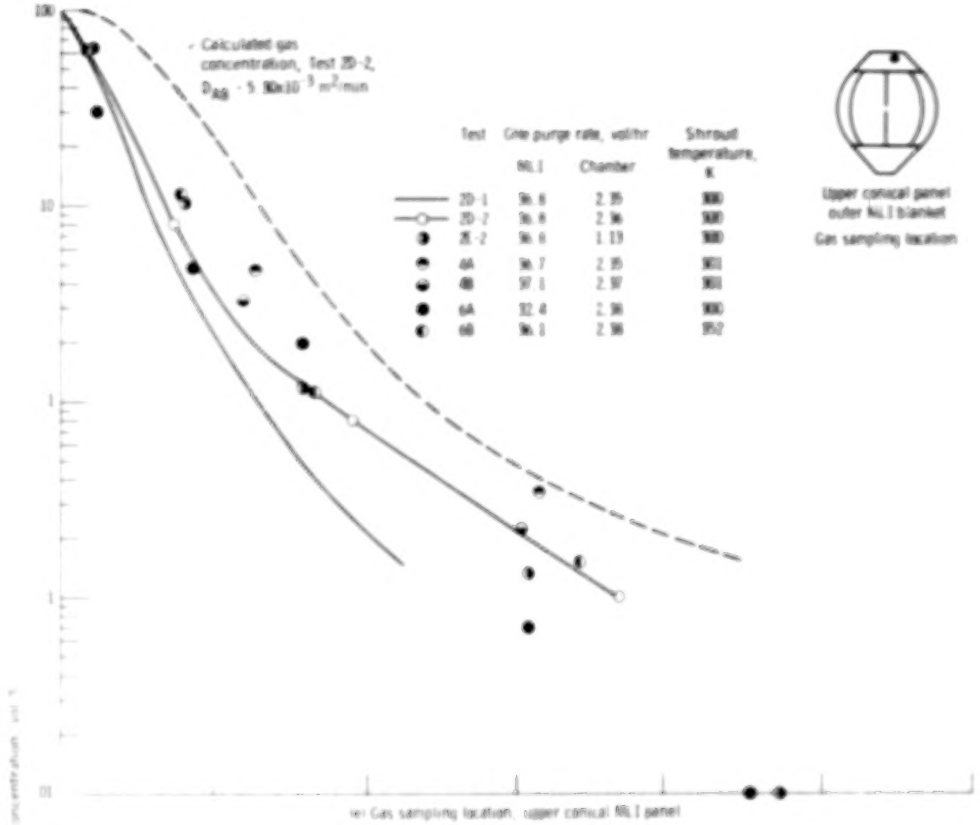
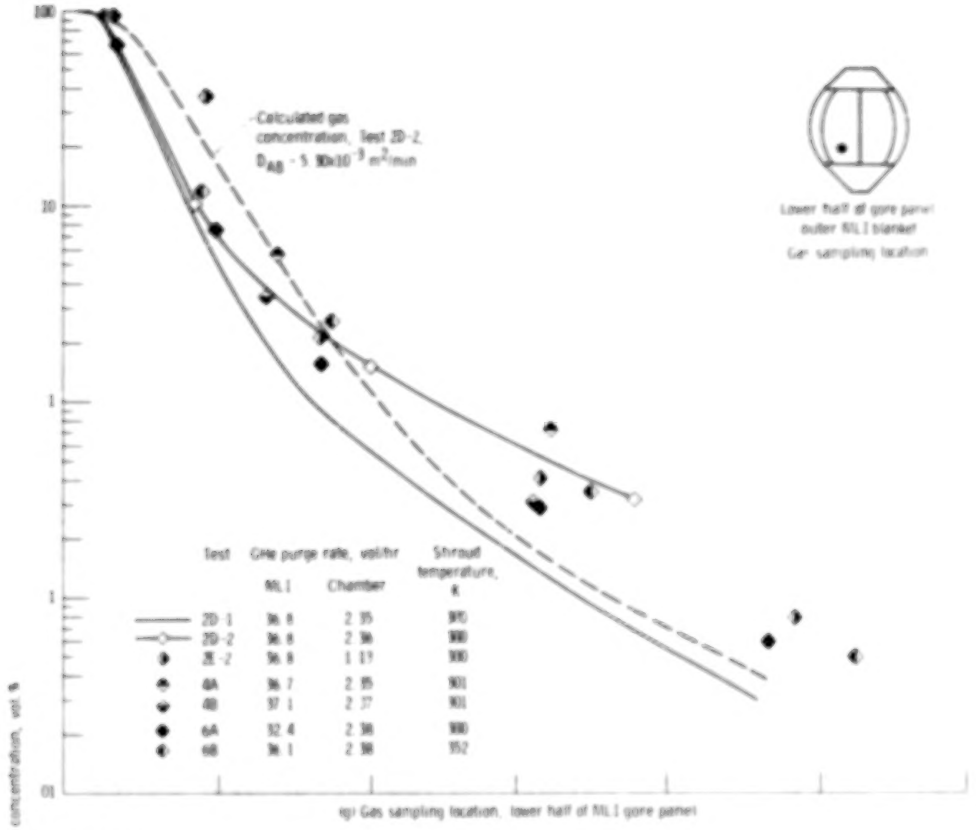
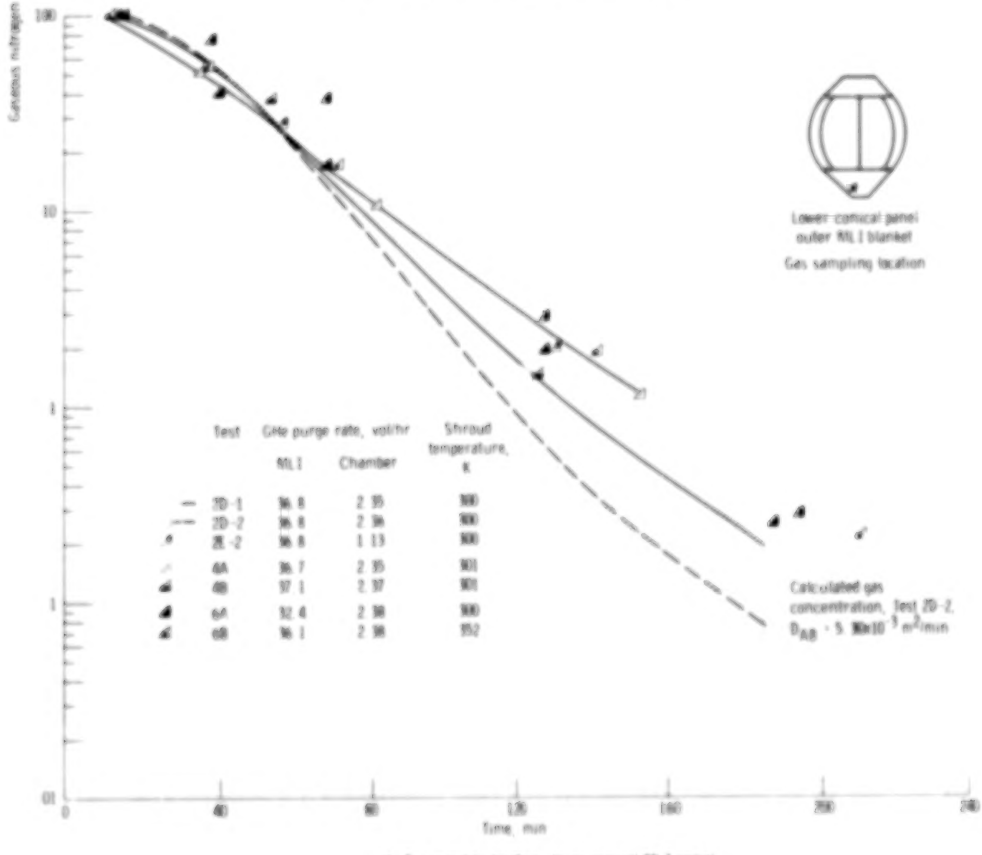

Calculated gas concentration, Test ZD-2, D_{AB} = 5.80x10^{-5} m^2/min
Test
Gas purge rate, volume/hr
MLI
Chamber
Shroud temperature, K
ZD-1 96.8 2.35 300
ZD-2 96.8 2.36 300
ZE-2 96.8 1.19 300
4A 96.7 2.35 301
4B 97.1 2.37 301
6A 92.4 2.36 300
6B 96.1 2.36 352
Upper conical panel outer MLI blanket
Gas sampling location
Gas sampling location, upper conical MLI panel
Calculated gas concentration, Test ZD-2, D_{AB} = 5.80x10^{-5} m^2/min
Test
Gas purge rate, volume/hr
MLI
Chamber
Shroud temperature, K
ZD-1 96.8 2.35 300
ZD-2 96.8 2.36 300
ZE-2 96.8 1.19 300
4A 96.7 2.35 301
4B 97.1 2.37 301
6A 92.4 2.36 300
6B 96.1 2.36 352
Upper half of gore panel outer MLI blanket
Gas sampling location
Time, min
Gas sampling location, upper half of MLI gore panel

Figure 37 - Continued



(g) Gas sampling location, lower half of NSLI gore panel



(h) Gas sampling location, lower conical NSLI panel

Figure 27 - Concluded.

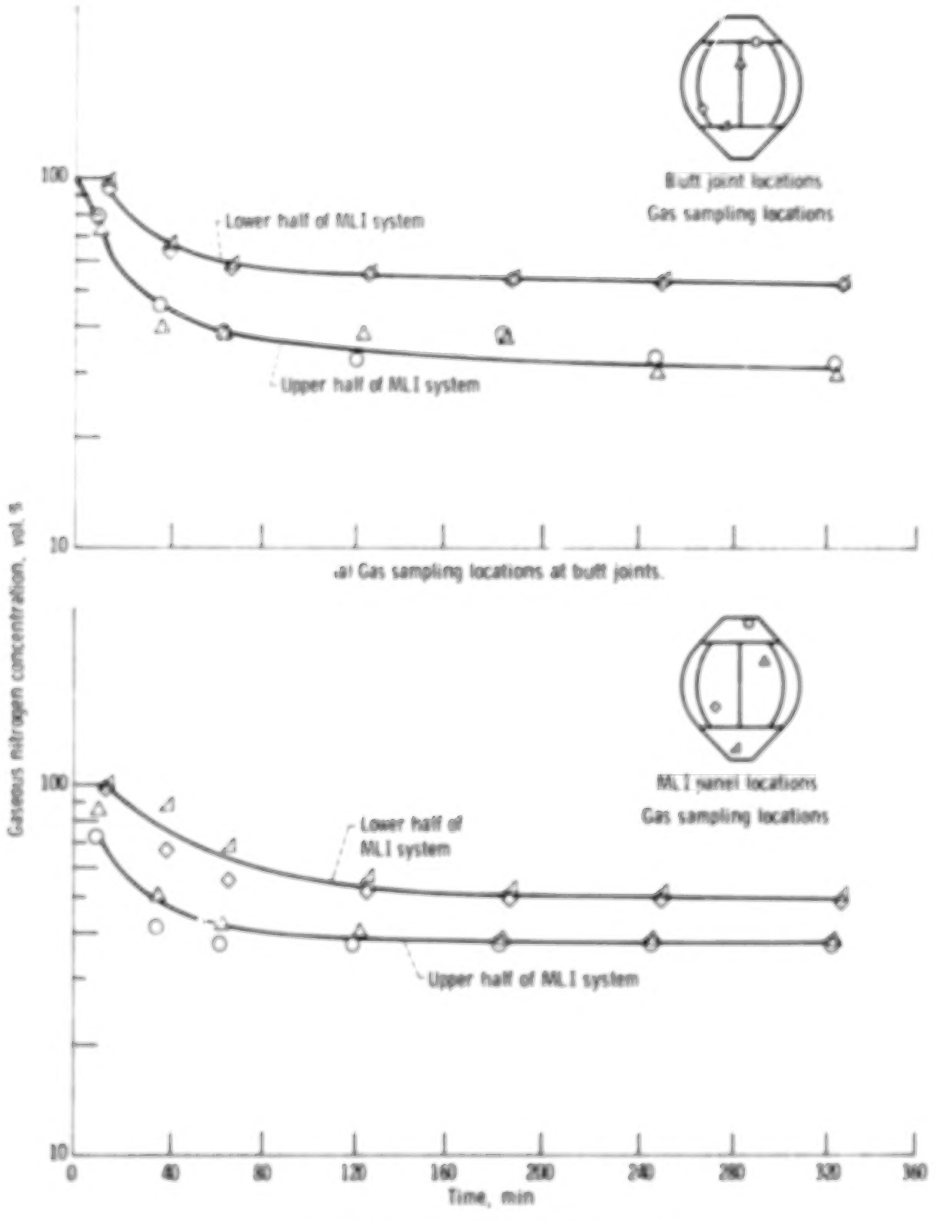


Figure 28. - Gaseous nitrogen concentration within MLI system. Test 2E-1; vacuum chamber GN_2 purge rate, 1.1 volumes per hour; MLI system GHe purge rate, 36.6 volumes per hour.

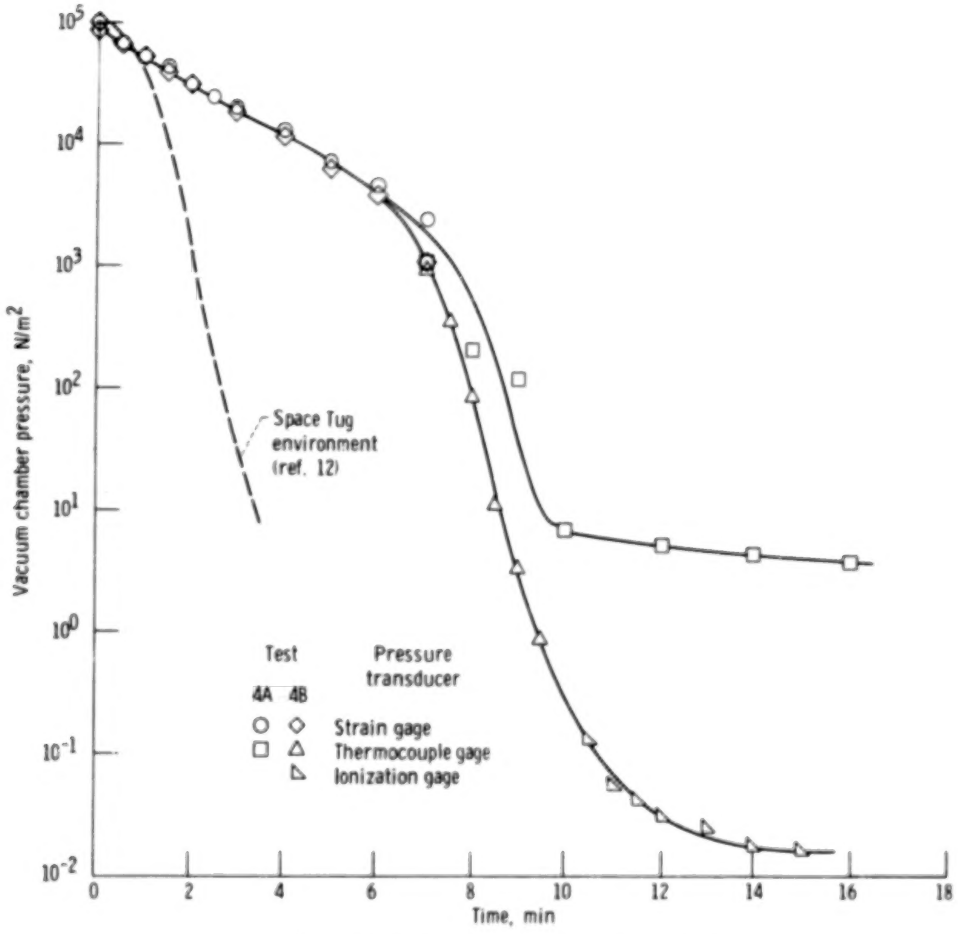


Figure 29. - Vacuum chamber pressure history during pumpdown.

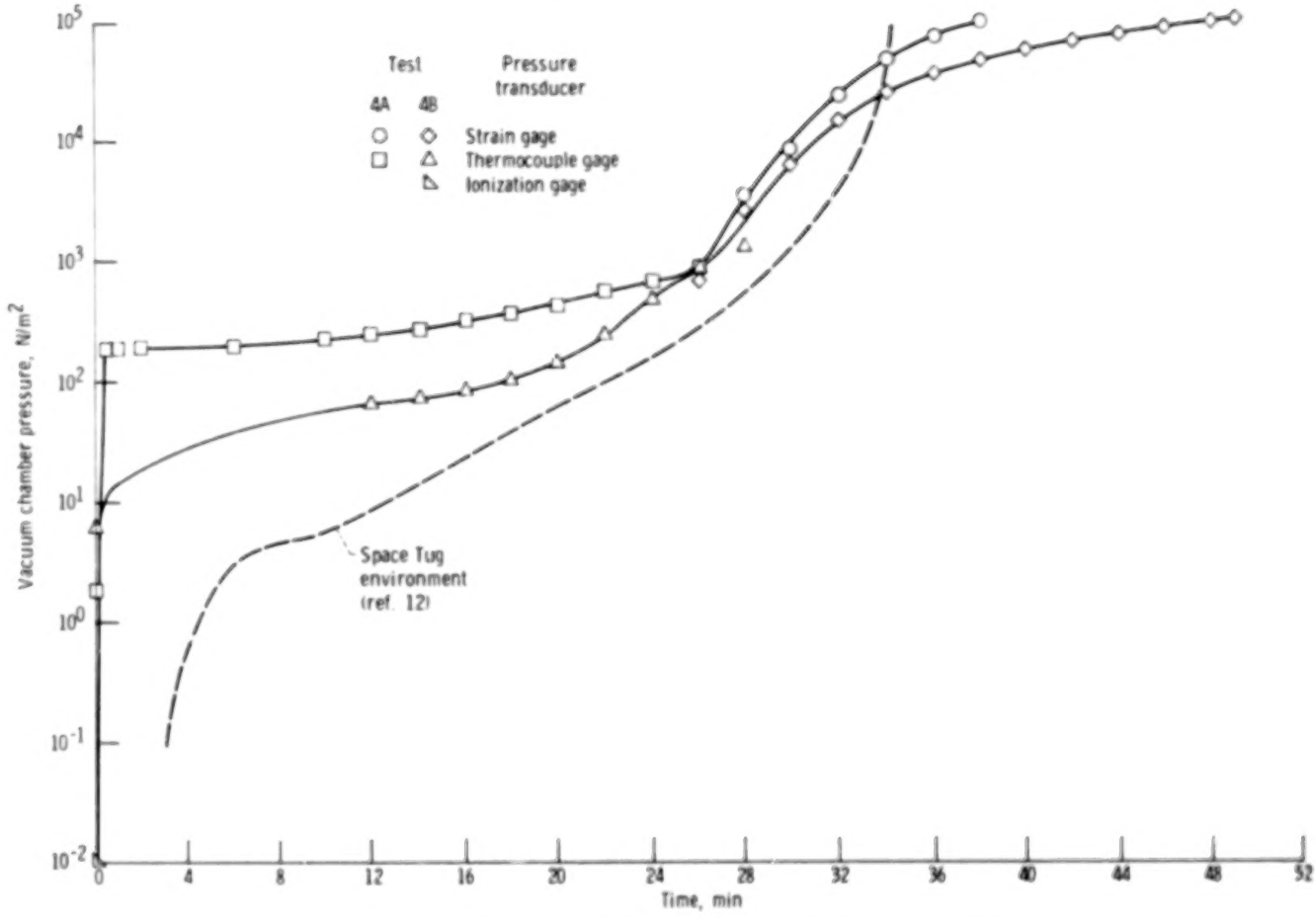


Figure 30. - Vacuum chamber pressure history during repressurization.

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16 Abstract

An experimental investigation was conducted to determine the gaseous helium purge characteristics of a multilayer insulation (MLI) system mounted on a spherical liquid hydrogen propellant tank 1.39 meters (4.57 ft) in diameter. The MLI consisted of two blankets of insulation each containing 15 double-aluminized Mylar radiation shields separated by double silk net spacers. The gaseous nitrogen initially contained within the MLI system and vacuum chamber was purged with gaseous helium introduced both underneath the MLI and into the vacuum chamber. The MLI panels were assumed to be purged primarily by means of gas diffusion. Overall, test results indicated that nitrogen concentrations well below 1 percent could be achieved everywhere within the MLI system. Typical times to achieve 1 percent nitrogen concentration within the MLI panels ranged from 69 minutes at the top of the tank to 158 minutes at the bottom of the tank. Predictions of gaseous nitrogen concentration agreed reasonably well with the measured values. Four space-hold (vacuum) thermal performance tests indicated no significant thermal degradation of the MLI system had occurred due to the purge tests conducted. The final measured heat input attributed to the MLI was 7.23 watts (24.7 Btu/hr) as compared to 7.18 watts (24.5 Btu/hr) for the initial baseline thermal performance test.

17 Key Words (Suggested by Author(s))	18 Distribution Statement		
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